utilization are shown for these two power sources, plus fossil steam and nuclear steam, in Figure 8-5[23]. Note that the figure is based on 1968 information; however, the relative comparison of these prime movers is still valid. These results do not include the cost impact of standards of performance for gas turbines. This impact is discussed in Section 8.4.1.3

As of January 1, 1974, six new IC engine generators were scheduled to be added to commercial power supplies -- five (total 32,840 kW) in 1974 and one (4415 kW) in 1975[24]. This compares with six engines (30,930 kW) added in 1973. The Federal Power Commission reports that as of April 1, 1977, 565,000 kW (39 units) of diesel and dual fuel generating capacity were scheduled to be installed in the period 1977 to 1986[25]. Since most of the IC engines used for electric power generation are owned by municipal utilities, which are generally smaller than the investor-owned utilities, it is possible that uncertainties in fuel availability and current high interest rates are preventing these smaller, municipally owned systems from raising the capital necessary to expand their systems. A spokesman for one manufacturer, however, stated that sales have picked up as the demand for additional power has reached critical level. In addition, another source believes that an increasing number of engines will be used for onsite power generation by municipalities and large industrial electricity users[26].

Large diesels are also used in nuclear powerplants, since these facilities are required to have emergency power available to flood the reactor core with water in the event of a reactor failure. Industry representatives (both manufacturers and users) have indicated that the high-power diesel engines have no effective competition for this market[27]. Due to the quick startup requirements for nuclear power (10 seconds and

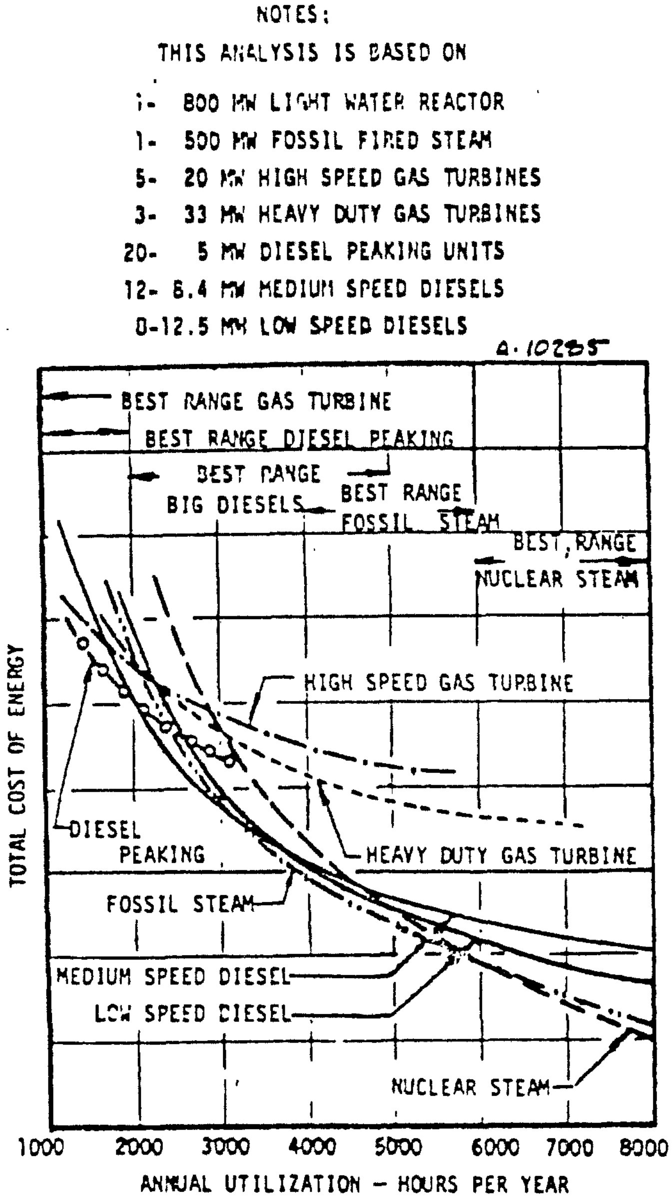


Figure 8-5. Chart shows relative cost data and most favorable operating ranges for the various types of generating facilities, as derived from one particular study (from Reference 23 -- costs for 1968).

load capability in 30 seconds), this service is almost exclusively met by large diesel engines. Since safety regulations require that there be at least two engines for each reactor, the best indicator of future engine needs by this market is a record of scheduled construction of nuclear power reactors. Table 8-6 shows the number of reactors scheduled for completion[1/]. This indicates a market for 338 to 382 high-power engines in the next 10 to 15 years. Although recent difficulties in raising capital and in proving the safety of reactors and spent fuel disposal have caused utilities to delay over 40 percent of the units under construction or on order and to cancel 5 to 10 percent, the Nuclear Regulatory Commission (formerly the Atomic Energy Commission) continues to project that 102,000 nuclear megawatts will be constructed by 1980 and 250,000 by 1985[30]. It should be recognized that the engines for a particular reactor may be purchased up to a year or two before the reactor becomes operational.

TABLE 8-6. PLANNED CONSTRUCTION OF NUCLEAR REACTORS

	Completed	Scheduled as of January 1, 1974					
	During 1973	1974	1975	1976	1977	1978	1979 & later
Reactors	7	27	10	7	12	11	102

Radar power stations are also served by reciprocating engines which maintain precise power characteristics over sizable load variations.

[1/]The source of this table[28] lists 169 units completed or scheduled for completion after 1973. Another source mentions that 191 units are currently under construction or on order.

Engines have also been in demand by flood control districts for pumping applications along the Mississippi Delta.

8.1.3.2 Markets for Dual-Fuel Engines

The concept of dual fuel operation was developed to take advantage of both compression ignition performance and inexpensive natural gas. These engines have been used almost exclusively for prime electric generation. Figure 8-6[31-34] illustrates, however, that shortages of natural gas and the 1973 oil embargo have combined to significantly reduce the sales of these engines in recent years. For example, sales of dual-fuel engines in 1971, 1972, 1973, 1974, and 1975 were 95, 74, 53, 17, and 35 units, respectively[35,36]. As discussed above, spokesmen for engine manufacturers stated that sales have recovered somewhat as demands for power have become critical and firm commitments for fuel are established.

8.1.3.3 Markets for Natural Gas Engines

The primary application of large gas engines during the past 5 years has been for oil and gas production. Figure 8-7[37-42], based on manufacturer's data from responses to the June 16, 1976 Section 114 Request for Information, illustrates that 75 to 80 percent of all gas engine horsepower sold during the past 5 years was used for this application. The primary uses are to power gas compressors for recovery, gathering, and distribution.

During this time, sales to pipeline transmission applications declined. Combined with standby power, electric generation, and other services (industrial and sewage pumping), these applications accounted for the remaining 20 to 25 percent of horsepower sales. The growth of oil and gas production applications during this period corresponds to the

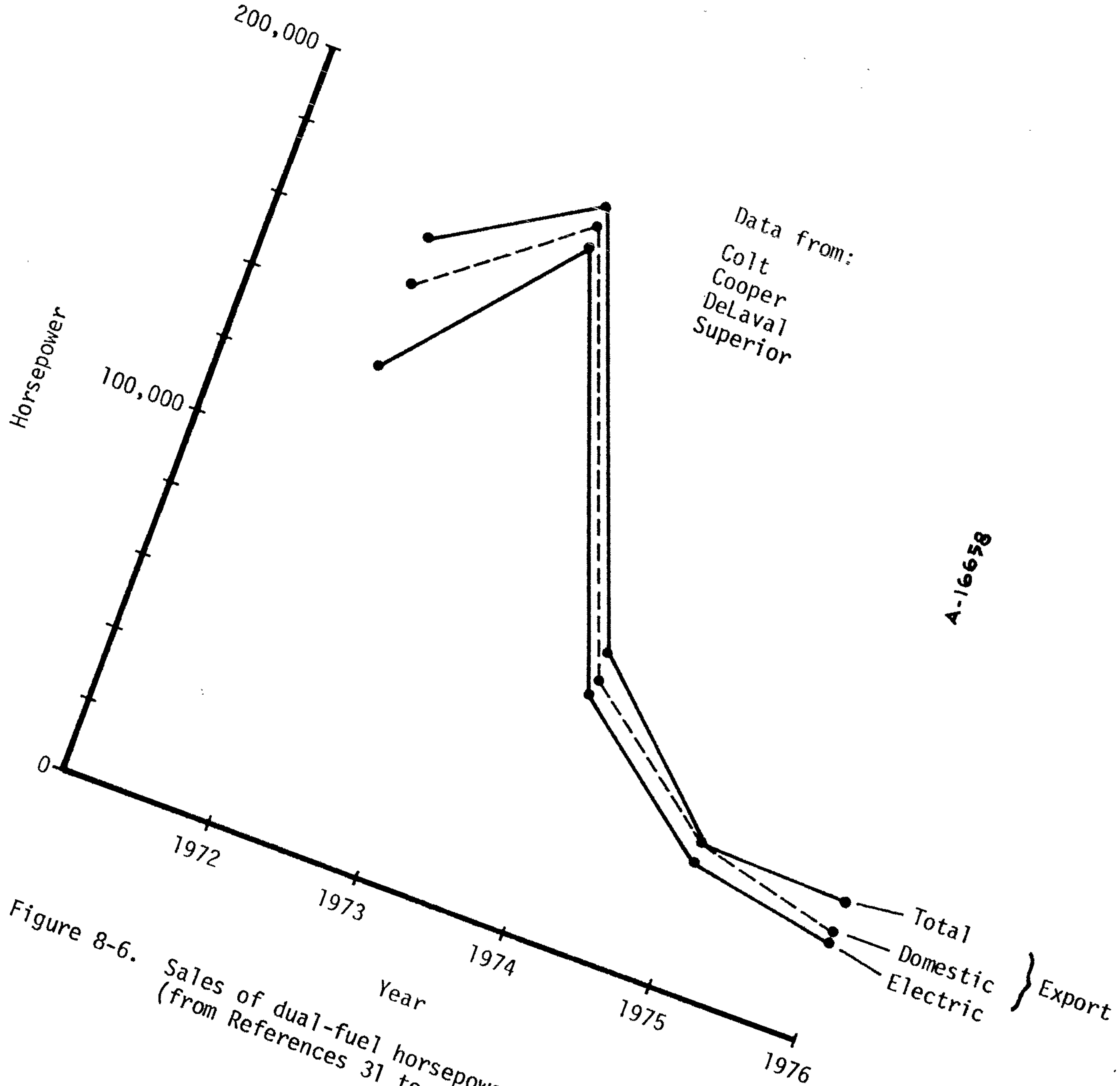


Figure 8-6. Sales of dual-fuel horsepower during the past 5 years (from References 31 to 34).

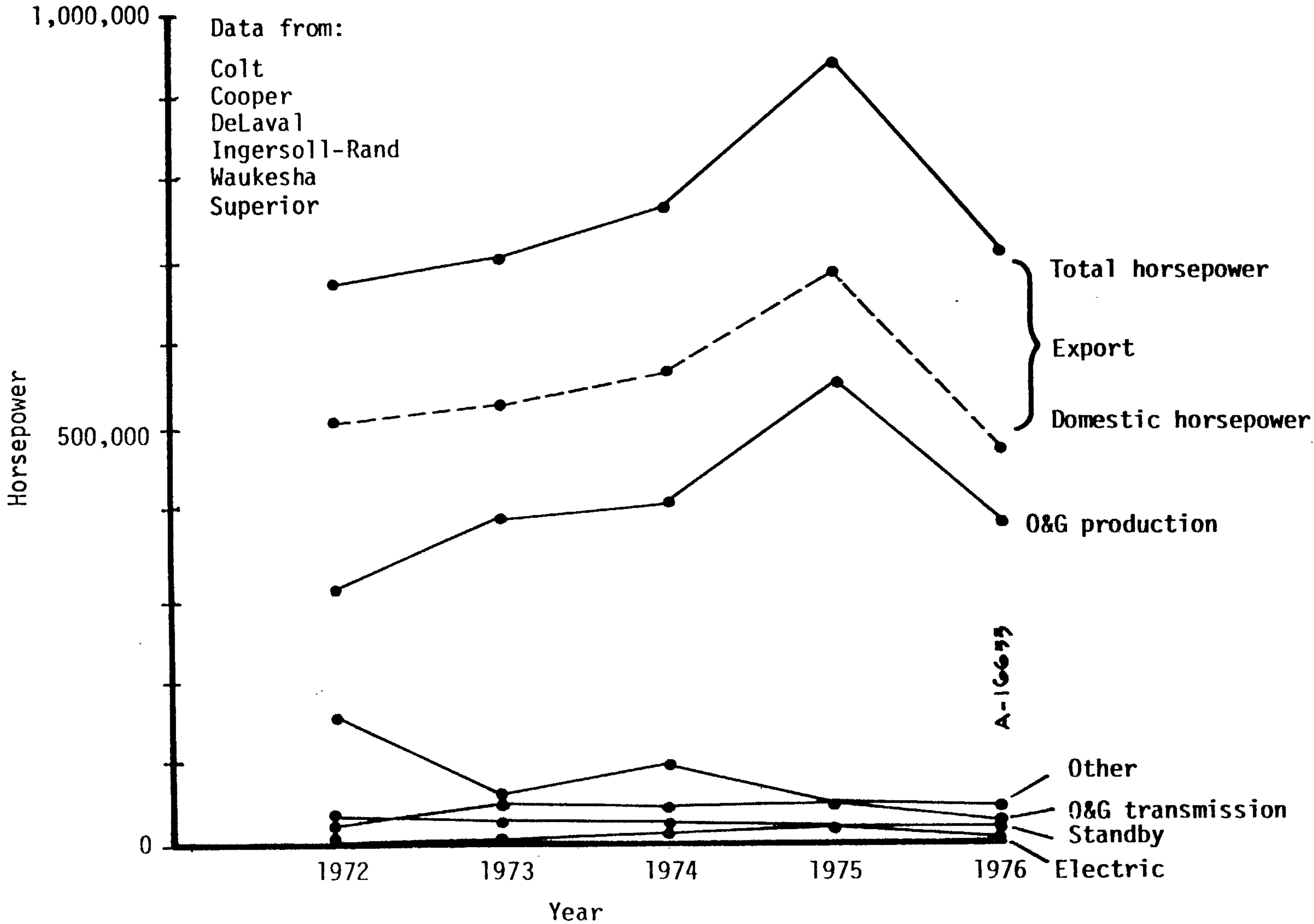


Figure 8-7. Sales of gas engine horsepower by application for the past 5 years (absolute levels shown for domestic applications, from References 37 to 42).

increasing efforts to find new, or recover marginal, gas reserves, and distribute them to our existing pipeline transmission network, and store in covered, underground reservoirs near cities for peak winter demands.

Figure 8-8 illustrates the number of gas engines sold for five size groups during the past 5 years. The large number of smaller than 500-hp engines that were sold during this period are primarily one or twocylinder engines used on oil well beam pumps and for natural gas well recovery and gathering. Most of the other, larger gas engines that were sold during this period ranged from 500- to 2000-hp. In 1976, approximately 400 engines in this size range were sold, primarily for oil and gas production (see Figure 8-7). Most of these gas engines were manufactured by Caterpillar, Cooper, Waukesha, and Superior Division of Cooper.

Historical sales data for pipeline transmission and field compressor stations (see Figure 8-9)[43] clearly indicate the recent market position for IC engines and gas turbines. Total sales of IC engines have been relatively constant since 1970, while total gas turbine sales have decreased dramatically with the recent slowdown of new pipeline construction. A breakdown of sales for transmission and field applications in 1975 (year ending June 15) is given below[44]:

Prime Mover	Turbine		Engine	
Compressor Horsepower	Transmission Stations	Field Stations	Transmission Stations	Field Stations
New	21,933	2,000	4,080	29,400
Additions	23,300	3,500	78,800	30,450
Total	45,233	5,500	82,880	59.850

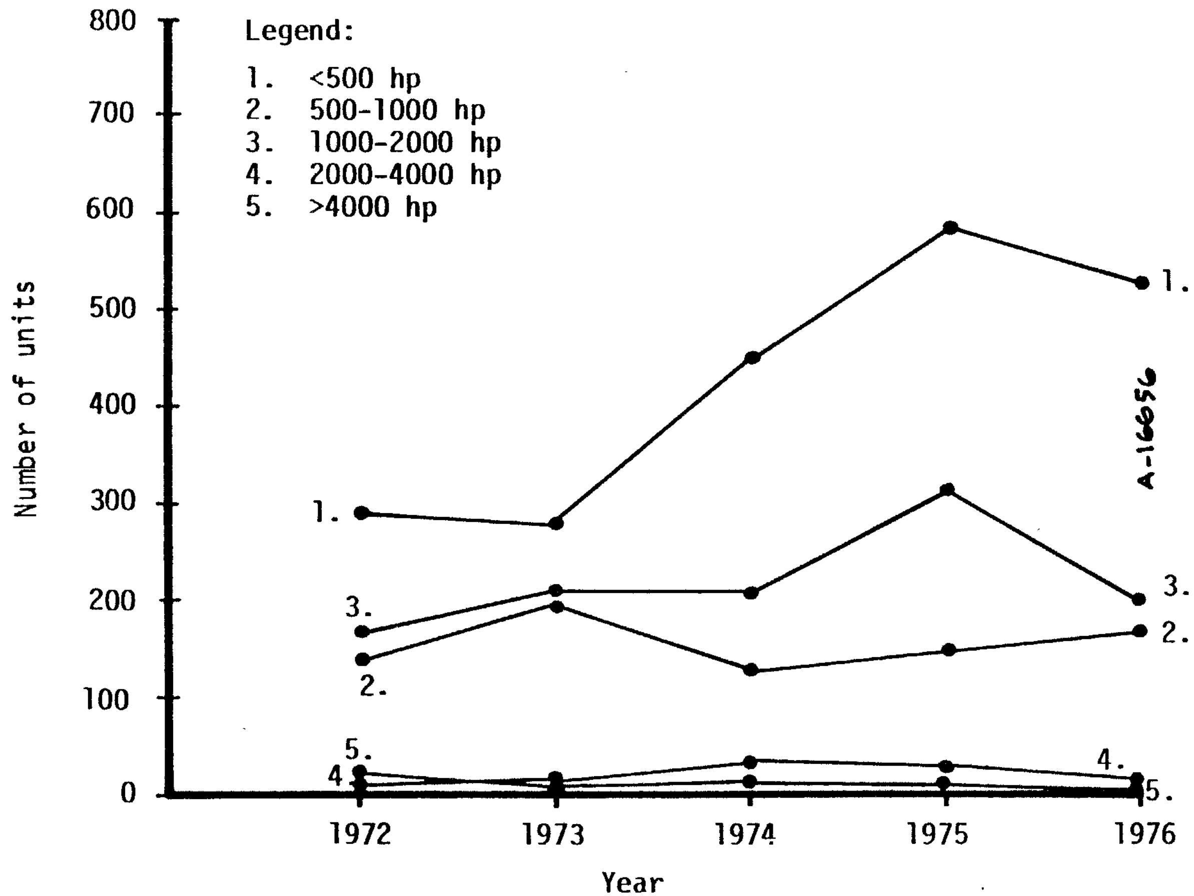


Figure 8-8. Size distribution of gas engines sold during the past 5 years.

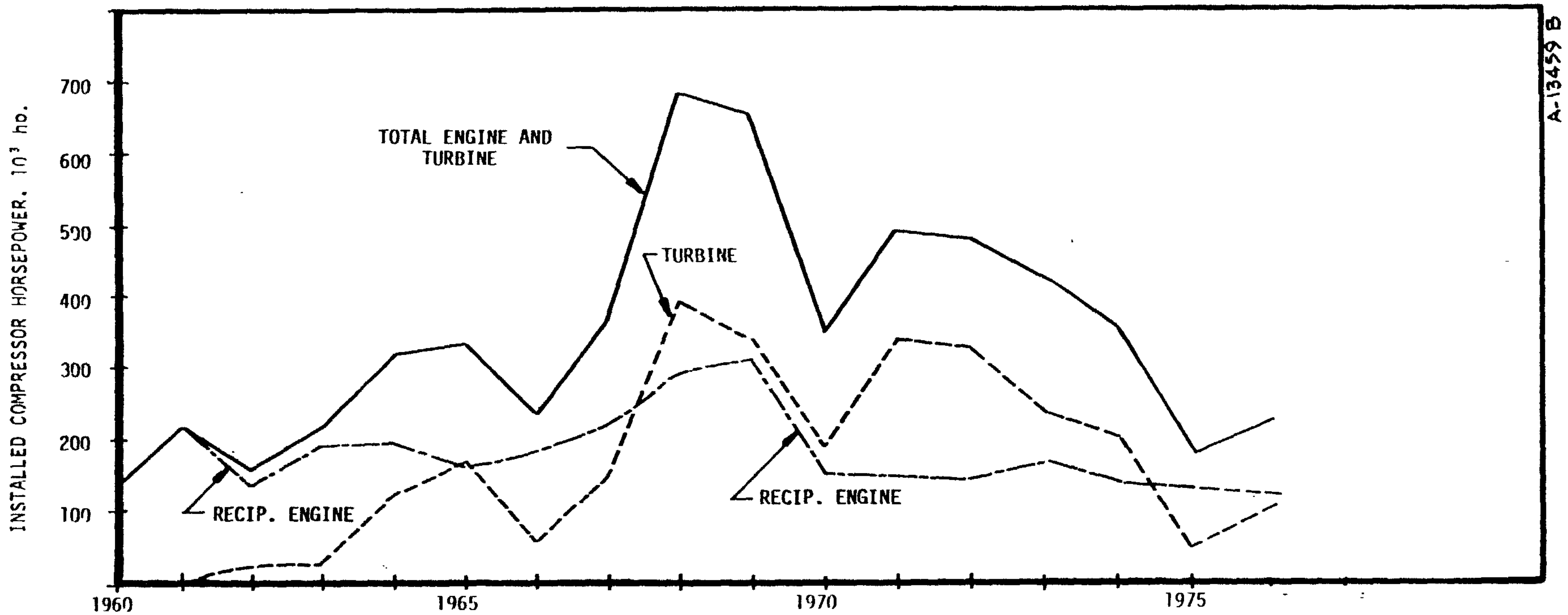


Figure 8-9. New and added compressor capacity on gas transmission pipelines (Reference 43).

These data indicate that new transmission pipeline projects are almost exclusively equipped with turbine-powered centrifugal compressors, while new field stations (gathering, recompression, storage) are powered by engine-driven reciprocating compressors. Widely varying loads are encountered in these latter applications, and therefore, engine-driven reciprocating compressors are better adapted to this service than are turbine-driven rotating compressors. In 1975 nearly 80 percent of the total sales of reciprocating horsepower was for additions to, or replacement of, existing compressor stations, while turbine sales were evenly divided between new and existing compressor stations. In some cases the gas turbine sales to existing stations have displaced reciprocating engines. This has occurred in growing compressor stations or in facilities where all the old engines reach retirement age at the same time and can be replaced more cheaply by one large turbine than by several reciprocating engines.

Engines used in pipelines are concentrated in the major gasproducing areas, such as the Gulf Coast, and along the major natural gas pipelines. Pipeline construction has dropped in the last several years, but applications to the FPC for pipeline construction increased during 1973 and the first half of 1974 as plans were made to exploit the natural gas discovered in Alaska[45]. If the percentage of compressor stations utilizing reciprocating engines remains the same as in the past, this will bring an increase in engine sales over the next several years as pipeline companies purchase compressors to move the gas. The exact impact is uncertain, however, as firm orders for equipment await final approval by the FPC.

According to one major western oil company, in the past 10 years there has been a movement away from reciprocating engines used in refinery operations to electric motors, steam turbines for high-load requirements, and, occasionally, fossil-fueled turbines[46]. Moreover, a plant manager from one of the major chemical processing firms, who utilizes large reciprocating engines to compress gases, believes that large power users will purchase gas turbines in the future for fuel conservation reasons. Most of these users can utilize the waste heat from the prime mover, and more of this energy can be recovered economically from one very large turbine than from several large engines[47].

Municipalities use high-power, spark-ignited engines to generate electricity from digester gas in sewage treatment plants and to pump water. Competition for these applications comes from gas turbines and electric motors. As with electric power generation, IC engines have an advantage over turbines for applications when fuel costs are a significant portion of annual costs. Engines are preferred over electric motors in areas where electricity is relatively more expensive than liquid or gaseous fuels and in applications such as sewage processing where a by-product (such as sewage gas) can be burned to supplement other fuels.

8.1.4 Balance-of-Trade

The U.S. Bureau of the Census (Department of Commerce) does not classify imported and exported IC engines into stationary and nonstationary applications. Furthermore, there are no priority reasons for assigning a breakdown by application to either imported or exported engines. Therefore, information on the balance-of-trade for the stationary engine market is limited to the following categories, for which the Department of Commerce does report data:

Imports: Engines for agricultural machines; compression ignition engines; aircraft engines; bus, auto, truck engines; outboard motors; and engines not elsewhere classified (NEC)

Exports: Diesel engines (automotive, marine, and NEC); gas engines other than turbines; outboard engines; gasoline engines (marine, automotive, and NEC); and IC engines NEC

Imported stationary engines would be included in the "Compression Ignition Engines," "Agricultural Machines," and "Not Elsewhere Classified" categories. These categories also include engines used for marine and construction applications. For this reason it is not possible to determine the exact number of imported stationary engines or the exact impact stationary source regulations would have on imports.

The classifications are less of a problem for exports because the categories are more narrowly defined. Furthermore, emission regulations on future domestic engines would only affect exported engines if the U.S. manufacturers added control devices to all their engines produced in the U.S. rather than maintaining two lines of engines -- one for regulated engines and one for unregulated engines. Table 8-7[48,49] gives import and export data for the appropriate categories of IC engines during the fiscal years 1969 to 1973.

Except for 1972, the trade balance for IC engines has been positive at about $60 million to $75 million per year and is improving. It is interesting to note that the average value of exported diesel engines is about six-times the average value of imported diesel engines, while the average value of exported gasoline engines is about one-third the average value of imported gasoline engines. Using 1971 Commerce Department price

TABLE 8-7. IMPORT AND EXPORT OF IC ENGINE CATEGORIES THAT INCLUDE STATIONARY APPLICATIONS[a]

		Exports			Imports[b]			Balance-of-Trade[c] ($1000)
		Quantity	Value ($1000)	Average Value ($)	Quantity	Value ($1000)	Average Value ($)	
Gasoline Engines	1969	1,000,911	52,858	52	276,438	25,795	93	28,429
	1970	858,688	49,964	56	325,696	36,432	112	14,700
	1971	761,912	42,375	56	425,779	41,153	97	6,097
	1972	976,601	51,930	53	620,925	57,524	92	(1,351)
	1973	1,703,460	83,673	49	330,224	49,190	148	37,168
Diesel Engines	1969	19,221	64,677	3,365	48,413	30,609	632	34,068
	1970	19,439	85,527	4,400	48,511	36,834	759	48,693
	1971	16,555	101,135	6,109	43,280	33,794	780	67,341
	1972	17,156	83,397	4,861	55,765	47,892	860	35,505
	1973	20,968	104,760	4,996	72,271	64,289	889	40,471
Gas Engines	1969	769	1,366	1,776	--	--	--	--
	1970	1,009	1,168	1,157	--	--	--	--
	1971	1,436	4,865	3,387	--	--	--	--
	1972	833	4,243	5,093	--	--	--	--
	1973	988	2,685	2,717	--	--	--	--
Total	1969	1,020,901	118,901		324,851	56,404		62,497
	1970	879,136	136,659		374,207	73,256		63,393
	1971	779,903	148,375		469,059	74,947		73,428
	1972	994,590	139,570		676,690	105,416		34,154
	1973	1,725,416	191,118		402,495	113,479		77,639

[a]These categories are Compression Ignition Engines and Engines NEC for imports; they are Diesel Engines NEC, Gas Engines other than Turbines, and Gasoline Engines NEC for exports (References 48, 49). These categories also include an unknown number of engines for mobile use.

[b]Gas engine imports are included in the figures for gasoline engine imports.

[c]Balance-of-Trade for gasoline and gas engines. Number in parenthesis means a deficit.

data for the value of engines produced in the U.S. as a function of their rated power, the following information can be derived for 1973 imports and exports[50].

	Diesel Engines		Gasoline Engines	
	Imports	Exports	Imports	Exports
Average value per engine, $	889	4996	148	49
Corresponding average hp	60	300	11	6

Thus, future imports of diesel engines should correlate with U.S. demand for small diesel engines. Most of the diesel-powered portable refrigeration units and underground mining machinery in the U.S. use imported diesel engines [51,52].

Since international markets for all capital equipment are highly competitive, trade balances of engines may be affected more by monetary exchange rates and tariff restrictions than by price changes due to emission control systems. Moreover, based on the average horsepower shown above, large-bore engines play an insignificant role in the import or export market of stationary reciprocating IC engines.

8.2 COST ANALYSIS FOR CONTROL OF NO_x EMISSSIONS

This section presents a discussion of the cost impact to the engine user and manufacturer of implementing the viable NO_x control options designated in Chapter 6. The costs to the engine user of purchasing and operating engines equipped with selected NO_x controls are discussed in Section 8.2.1. The costing was done on the basis of information supplied by the manufacturers and users, and is applied to a group of "model" engines that are typical of those used in a particular application.

In Section 8.2.2 the costs to the manufacturers for the implementation of the alternative NO_x controls (presented in Chapter 6) are discussed. These cost considerations include additional manufacturing associated with adaptation of controls to existing designs and the costs of engineering, tooling, and verifying the effectiveness of a particular control approach.

Section 8.2.3 presents those costs associated with emerging control techniques. In Sections 8.2.4, 8.2.5 and 8.2.6 costs associated with fuel pretreatment, modified facilities, and reconstructed facilities, respectively, are identified.

8.2.1 New Engines

The application of NO_x controls will affect costs to the engine manufacturer and the engine user. The degree of the effect will depend upon both the amount of reduction applied and the type of control applied. As was shown in Section 6.3, various control approaches affect initial costs, fuel consumption, and maintenance differently. Furthermore, manufacturers of stationary engines may incur different costs to achieve a given NO_x reduction depending on a number of factors including: (1) their degree of advancement in emissions testing, (2) the uncontrolled emission rates of their engines, and (3) the necessary R&D required to produce engines which can meet proposed standards of performance. Therefore, the discussion of incremental costs to employ NO_x controls for manufacturers and engine users will be treated separately. This section will be restricted to the discussion of incremental costs incurred by engine users, and Section 8.2.2 will discuss NO_x costs related to engine manufacturers.

To illustrate the effect of NO_x controls on costs, "model" engines will be selected to represent major end users of diesel, dual-fuel, and natural gas engines. Baseline costs, comprised of investment and operating expenses, will be established for each model. Computations for these model units will then be used to illustrate the range of incremental costs to the user resulting from the application of the NO_x control systems described in Section 6.2. These incremental costs will be illustrated for several control systems that achieve any one of three levels of NO_x reduction (20 percent, 40 percent, and 60 percent). This approach is not intended to be a comprehensive cost analysis of all possible NO_x control systems; rather it is intended to illustrate a range of costs that an engine user would incur to achieve a given level of NO_x reduction. The discussions are subdivided by major end uses, since engine types and costs are unique to each end use.

Section 8.2.1.1 briefly describes the models selected to represent major engine applications. The cost analysis methodology is then discussed in Section 8.2.1.2, and the results of the cost analysis are presented in Section 8.2.1.3.

8.2.1.1 Model Engines

Four model engines have been selected to represent the major applications of diesel, dual-fuel, and natural gas engines. (The applications were described in Section 8.1.3) The following paragraphs briefly describe these models.

Diesel Engine Model: Electrical Generation

As described in Section 9.3.1, affected diesel engines are large-bore, exceeding a displacement of 560 cubic inches per cylinder. Typically these engines are used as prime movers for electrical generators in municipal utilities. These engines operate from 6000 to 8000 hrs/year (baseload) and consume approximately 7000 Btu/hp-hr of operation. Manufacturers of these engines include Alco, Colt, Cooper and Superior Division (of Cooper), DeLaval, and ElectroMotive division of General Motors.

Dual-Fuel Engine Model: Electrical Generation

These engines are nearly identical to the diesel engines except that they burn predominantly natural gas (typically 95 percent of the total fuel heating value). In general, these engines operate more efficiently than their diesel counterparts, consuming 6500 Bth/hp-hr of operation. Manufacturers of affected dual-fuel engines include Colt, Cooper and Superior Division (of Cooper), and DeLaval.

Gas Engine Model: Oil and Gas Transportaion

These engines are installed on pipeline compressors for long-range transportation of natural gas. They generally exceed 1000 hp, averaging 3000 to 4000 hp. Typical annual usage is 8000 hrs, and representative fuel consumption is 7000 Btu/hp-hr. Manufacturers of gas engines for this application include Colt, Cooper and Superior Division (of Cooper), DeLaval, and Ingersoll-Rand.

Gas Engine Model: Oil and Gas Production

These engines are installed on compressors that gather, store, process, or distribute gas from gas production fields. (These engines generally burn gas that has been treated to reduce the sulfur content.) As described in Section 9.3.3, engines that would be affected by proposed standards of performance range from 300 to 2000 hp. An average size engine is about 1000 hp and consumes about 8000 Btu/hp-hr. These engines are manufactured primarily by Caterpillar, Cooper and Superior, Waukesha, and Ingersoll-Rand.

8.2.1.2 Costing Model for Users of Stationary IC Engines

The objective of the cost analysis is to estimate how an engine user's life cycle costs will change with the application of NO_x controls for the model diesel, dual-fuel, and gas engines described in Section 8.2.1.1. The following paragraphs describe the cost analysis approach and the basic assumptions that are used to estimate the incremental costs created by NO_x controls. Section 8.2.1.3 will then present the results of the cost analysis.

Methodology

The costs of owning and operating a large-bore engine can be represented as follows:

$$TAC = AIC + M + F$$

where TAC = total annual cost of ownership and operation of engine

AIC = annualized initial cost = initial engine cost x capital recover factor (CRF)

M = maintenance costs

F = fuel and lubrication costs

The annualized initial cost includes capital recovery of the initial investment (assuming 100 percent debt financing), depreciation, property taxes, and insurance. Capital recovery rates typically range from 15 to 25 percent. Conversations with industry spokesmen indicate that a rate of 20 percent is appropriate[2/] for estimating installed engine costs for electrical generation, gas production, and gas transportation applications[(53,54)].

The procedure for computing the incremental costs of various NO_x control techniques is as follows:

- Estimate the increase in the costs of AIC, M, and F due to NO_x controls
- Compute the increase in the total annual cost, TAC
- Present the results as $(TAC_c - TAC_u)/TAC_u \times 100$ = percent increase in TAC where c = controlled and u = uncontrolled

<u>Basic Costs and Parameters for Cost Analysis</u>

Table 8-9 summarizes the basic inputs for computing the total annual costs of uncontrolled engines. As this table indicates, the costs will be presented in a brake specific format, that is, in \$/hp-hr. The initial costs are normalized by the output power and usage rate to obtain \$/hp-hr. This format makes it possible to compare ownership costs for a number of differently sized engines that are used in the same applications. This format also permits a direct comparision of the incremental NO_x control costs among engines using different fuels.

2/ CRF computed assuming a 30-year physical life, 20-year accounting life, 100-percent debt financing, 10-percent interest on debt, and 4-percent fixed capital expense (e.g., property tax, insurance, and direct overhead). On these assumptions, debt service is 10.6 percent, depreciation 5 percent, and fixed capital expense 4 percent a total of 19.6 percent.

As shown in Table 8-8, typical initial costs for diesel and dual-fuel electrical generation and oil and gas transmission engines are \$150[55]. (This cost is for the engine only, F.O.B..) Costs for gas production engines are estimated at \$50/hp and are representative of engines sold by Caterpillar and Waukesha[56]. Total capital investments for installed electrical generation stations are approximately \$300/hp (1976)[57]. Current investments for installed gas transmission compressor installations range from \$318 to \$575/hp, and range up to \$584/hp for gas field stations[58]. Thus, the cost increases computed in this section will be considerably smaller when expressed as a percentage of the total application investment.

Maintenance costs for these engines have been estimated based on information supplied by engine manufacturers. These costs are typical of engines that operate continuously at rated load.

Fuel costs assumed for the electrical generation applications are representative of costs of distillate oil and natural gas transported both intra- and interstate. (The current (1978) regulated price of interstate gas is \$1.48 per Mcf.) Lower gas costs have been assumed for oil and gas production and transportation applications since gas companies own these facilities and pay less for the gas. In addition, average gas costs for these companines are a composite of contracted supplies of gas that span several years[59]. Fuel consumption estimates are average values based on the data presented in Section 4.3.1. Note that this analysis assumes baseload or continuous annual operation ($\approx$8000 hr/yr). Figure 8-9 illustrates the relative proportion of each of these items relative to total uncontrolled costs. Fuel and lubrication costs are the largest fraction

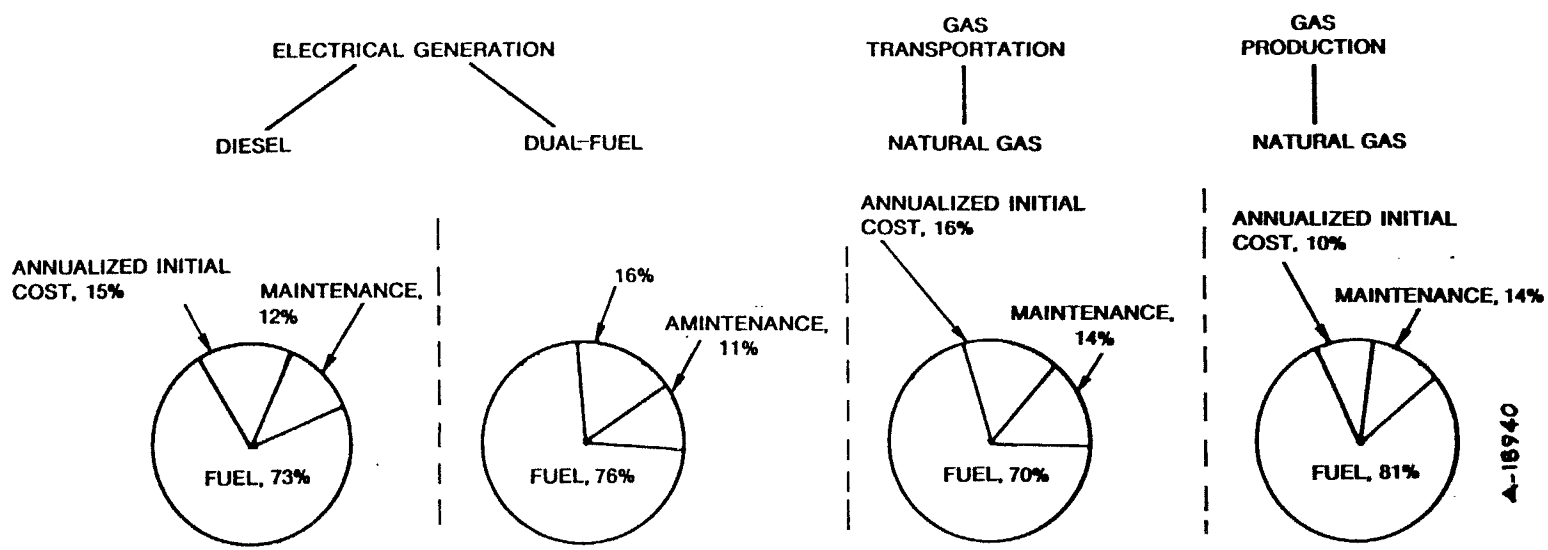
TABLE 8-8. BASELINE COST PARAMETERS FOR LARGE-BORE ENGINES

COST PARAMETERS	ENGINE MODELS			
	DIESEL (Electrical Generation)	DUAL-FUEL (Electrical Generation)	NATURAL GAS (Oil & Gas Transport)	(Oil & Gas Production)
Initial Cost[a,b], \$/hp	150	150	150	50
Capital Recovery Factor	0.2	0.2	0.2	0.2
Annual Usage, hr/yr	8000	8000	8000	8000
Maintenance[a]				
Parts, \$/hp-hr	0.0012	0.0012	0.0012	0.0012
Labor, \$/hp-hr	0.0018	0.0018	0.0018	0.0018
Total, \$/hp-hr	0.0030	0.0030	0.0030	0.0030
Fuel Cost[c], $\$/10^6$ Btu	2.50	3.00	2.00	2.00
Fuel Consumption, Btu/hp-hr	7000	6500	7000	8000
Lubrication[a], % Fuel Cost	5	10	10	10

[a]Aggregated from confidential communications with engine manufacturers.

[b]Initial cost divided by annual usage (8000 hr) and multiplied by the capital recovery factor (0.2) gives annualized cost in \$/hp-hr.

[c]Fuel cost calculations for dual-fuel units assume fuel consumption is 100% gas. All fuel costs based on 1977 information.



TAC = TOTAL ANNUAL COST
TAC = AIC + M + F
AIC = ANNUALIZED INITIAL COST
M = MAINTENANCE
F = FUEL AND LUBRICATION

Figure 8-10. Relation of initial maintenance and fuel costs to total costs for major applications of large-bore engines.

of total costs, accounting for 70 to 80 percent of the total. The variation is a result of the different engine and fuel costs assumed for each of the model applications.

The capital and maintenance cost increases resulting from the application of NO_x controls are estimated in Table 8-9. These estimates were aggregated from information supplied by engine manufacturers or vendors of auxiliary equipment. Increases in fuel consumption will be estimated for various control techniques based on the information given in Table 6-4 of Section 6.2.

8.2.1.3 Results of Cost Analysis

A cost analysis based on the preceding discussion was performed for each of the four model engines described in Section 8.2.1.1. Total annual cost penalties (as a percentage of total uncontrolled costs) were computed for each model engine and alternative level of NO_x reduction (i.e., 20-, 40-, and 60-percent reduction) for the control techniques that were discussed in Section 6.2. Table 6-4 is repeated here as Table 8-10 to illustrate those techniques and their fuel penalties for each level of control alternative and fuel type.

Fuel penalties are the major factor affecting cost increases for high usage engines. Table 8-10 shows that fuel penalties increase with increasing level of control. They also vary with control type. For example, derating results in substantial penalties (>10 percent) for NO_x reductions greater than 20 percent. Retard, manifold air cooling, and air-to-fuel controls, however, generally achieve NO_x reductions at a penalty less than 10 percent. It should be noted that the decrease in data at the 60 percent NO_x reduction level is the result of both: (1) manufacturer's inexperience with the application of controls to the extent

TABLE 8-9. COST INCREASES TO THE ENGINE USER RESULTING FROM NO_x CONTROL[a]

CONTROL	CAPITAL	MAINTENANCE
Retard	None	33% increase in base cost due to 25% reduced service life of exhaust valves for dual-fuel engines
Air-to-Fuel	None	Increase of 0.0001/hp-hr for increased cleaning of turbochargers
Derate	Increase by ratio of rated power to derated power (to compensate for power loss)	Increase by ratio of rated power to derated power (more units or cylinders to service)
Manifold Air Temperature Reduction	Increase engine costs 1.5% to acheive 100°F inlet air. Larger heat exchangers cost assumes engine equipped with intercooler	D, DF: Increase \$0.0005/hp/hr for cooling water chemical treatment (cooling towers)[b] G: Increase \$0.0001/hp-hr for increased service of radiator and aftercooler[c]
External Exhaust Gas Recirculation	Increase engine cost 5% for plumbing, heat exchanger and controls for 10-12% recirculation.	Double parts for diesel engines[d] Triple parts for dual-fuel and gas engines[d]

[a]Aggregated from confidential communications with engine manufacturers.

[b]Cooling water from cooling towers for diesel and dual-fuel engine must be treated to prevent sludge and scale buildup due to water "hardness".

[c]Closer tolerances to achieve lower manifold air temperature will require more frequent cleaning and servicing of radiators and intercoolers (or aftercoolers) of gas engines.

[d]Diesel unit has fixed rate of EGR, dual-fuel, and gas units have a variable rate of EGR. Charge for parts includes periodic replacement of the EGR system and its controls.

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TABLE 8-10. NO_x CONTROL TECHNIQUES THAT ACHIEVE SPECIFIC LEVELS OF NO_x REDUCTION

NO_x Reduction	Diesel		Dual Fuel		Natural Gas	
	Control (amount)	ΔBSFC,[a] %	Control (amount)	ΔBSFC,[a] %	Control (amount)	ΔBSFC,[a] %
20%	Retard (2 to 4°)	0 to 4	Retard (2 to 3°)	1 to 3	Retard (4 to 5°)	1 to 4
	External EGR (7%)	0	Manifold air cooling	1	Manifold air cooling	0
	Derate (25 to 50%)	3 to 5	External EGR (10%)	1	External EGR (4%)	0
	Air-to-fuel change (25%)	10	Derate (12 to 25%)	0 to 8	Derate (5 to 35%)	2 to 6
	Retard & manifold air cooling	0 to 1	Air-to-fuel changes (5 to 10%)	0 to 2	Air-to-fuel change (5%)	0-2
	Retard & manifold air cooling & air-to-fuel change					
40%	Retard (7 to 8°)	4 to 8	Retard (5°)	2	Retard (10°)	2
	Derate (50%)	14 to 17	Manifold air cooling	1	Derate (10 to 50%)	2 to 24
	Air-to-fuel change & manifold air cooling	3 to 5	Derate (30 to 50%)	4 to 8	Air-to-fuel change (7%)	2
	Retard & air-to-fuel change		Air-to-fuel change (10%)	2	Retard & manifold air cooling & air-to-fuel change	7
			Retard & manifold cooling	3		
60%	Retard (16°)	19 to 24	Retard (6°)	2	Derate (10 to 50%)	2 to 22
	Retard & air-to-fuel change	21	Derate (50%)	12	Air-to-fuel change (8 to 12%)	2 to 5
			Retard & air-to-fuel change	1 to 3	Retard & manifold air cooling & air-to-fuel change	7

[a] ΔBSFC = increase in brake specific fuel consumption.

necessary to achieve that level, and (2) in some cases the inability of a particular control approach to achieve reductions at this level.

The differential control costs for the techniques shown on Table 8-10 are tabulated in Tables 8-11 to 8-14 for the four end use applications described above. Table 8-15 is a summary of these cost penalties. In general, retard, manifold air cooling, air-to-fuel change, or some combination of these achieved 60-percent NO_x reductions for less than a 10-percent cost penalty for each application except diesel/electric generation. The cost penalty for the diesel/electric generation, 60-percent NO_x reduction category, however, is based on data from tests of only one engine model; therefore this result may not be representative of costs for other engine models.

The data in Table 8-15 indicate a wide variation in cost penalty at any level of NO_x reduction. Moreover, average cost penalties are less than 6 percent (with the exception of diesel engines) for a 60-percent NO_x reduction. Nevertheless, average cost penalties increase as the level of NO_x reduction increases.

Since average uncontrolled NO_x emission rates from engines of different manufacturers vary, cost penalties to achieve a given alternative performance standard will also vary among manufacturers. These differential costs are important to identify so that potential economic impacts in various end use markets can be identified (see Section 8.4.1).

Table 8-16 illustrates the cost penalties for each manufacturer and fuel type for each of the three alternative levels of performance standards. In general, the maximum cost penalty for any fuel is less than 10 percent with the exception of the 40- and 60-percent reduction levels for diesel engines. The data for gas engines do not indicate differential

TABLE 8-11. COST OF ALTERNATIVE NO_x CONTROLS FOR DIESEL ENGINES FOR ELECTRICAL GENERATION

NO_x Control % Reduction		Cost Component[a]	Retard (R)		Derate (D)		External EGR		Air-to-Fuel (A)		R+M		R+M+A		R+A		A+M	
		$/hp-hr	$/hp-hr	%Chg	$/hp-hr	%Chg	$/hp-hr	%Chg	$/hp-hr	%Chg	$/hp-hr	%Chg	$/hp-hr	%Chg	$/hp-hr	%Chg	$/hp-hr	%Chg
20%	Low	AIC	0.00375	0	0.005	33	0.00394	5	0.00375	0	0.00381	1.5	0.00381	1.5				
		M	0.003	0	0.004	33	0.0042	40	0.0031	3	0.0035	17	0.0035	17				
		F	0.01838	0	0.01893	3	0.01838	0	0.02022	10	0.01838	0	0.01856	1				
		TAC	0.02513	0	0.02738	9	0.02652	6	0.02707	8	0.02569	2	0.02587	3				
	High	AIC	0.00375	0	0.0075	100												
		M	0.003	0	0.0060	100												
		F	0.01912	4	0.01930	5												
		TAC	0.02587	3	0.03280	31												
40%	Low	AIC	0.00375	0	0.0075	100									0.00375	0	0.00381	1.5
		M	0.003	0	0.006	100									0.0031	3	0.0035	17
		F	0.01912	4	0.02095	14									0.01930	5	0.01893	3
		TAC	0.02587	3	0.03445	37									0.02615	4	0.02624	4
	High	AIC	0.00375	0	0.0075	100												
		M	0.003	0	0.006	100												
		F	0.01985	8	0.02150	17												
		TAC	0.02660	6	0.03500	40												
60%	Low	AIC	0.00375	0														
		M	0.003	0														
		F	0.02187	19														
		TAC	0.02862	14														
	High	AIC	0.00375	0											0.00375	0		
		M	0.003	0											0.0031	3		
		F	0.02279	24											0.02224	21		
		TAC	0.02954	18											0.02909	16		

[a]AIC = Annualized initial cost
M = Maintenance cost
F = Fuel and lubrication cost
TAC = Total annualized cost

TABLE 8-12. COST OF ALTERNATIVE NO_x CONTROLS FOR DUAL-FUEL ENGINES FOR ELECTRICAL GENERATION

NO_x Control % Reduction		Cost Component[a] $/hp-hr	Retard (R) $/hp-hr	Retard (R) %Chg	Mnfd Cooling (M) $/hp-hr	Mnfd Cooling (M) %Chg	External EGR $/hp-hr	External EGR %Chg	Derate (D) $/hp-hr	Derate (D) %Chg	Air-to-Fuel (A) $/hp-hr	Air-to-Fuel (A) %Chg	R+M $/hp-hr	R+M %Chg	R+A $/hp-hr	R+A %Chg
20%	Low	AIC	0.00375	0	0.00381	1.5	0.00394	5	0.00426	14	0.00375	0				
		M	0.004	33	0.0035	17	0.0054	80	0.00341	14	0.0031	3				
		F	0.02168	1	0.02168	1	0.02168	1	0.02146	0	0.02146	0				
		TAC	0.02943	4.3	0.02899	2.8	0.03102	10	0.02973	3.3	0.02831	.4				
	High	AIC	0.00375	0					0.005	33	0.00375	0				
		M	0.004	33					0.004	33	0.0031	3				
		F	0.02210	3					0.02318	8	0.02188	2				
		TAC	0.02985	5.8					0.03218	14.1	0.02873	1.8				
40%	Low	AIC	0.00375	0	0.00381	1.5			0.00536	43	0.00375	0	0.00381	1.5		
		M	0.004	33	0.0035	17			0.00429	43	0.0031	0	0.0035	17		
		F	0.02188	2	0.02168	1			0.02233	4	0.02188	2	0.02210	3		
		TAC	0.02963	5	0.02899	2.8			0.03177	13.3	0.02873	1.8	0.02941	4.3		
	High	AIC							0.0075	100						
		M							0.006	100						
		F							0.01159	8						
		TAC							0.03668	30						
60%	Low	AIC	0.00375	0					0.0075	100					0.00375	0
		M	0.004	33					0.006	100					0.0041	36
		F	0.02188	2					0.02404	12					0.02168	1
		TAC	0.02963	5					0.03754	33					0.02953	4.7
	High	AIC													0.00375	0
		M													0.0041	36
		F													0.02110	3
		TAC													0.02995	6.2

[a]AIC = Annualized initial cost
M = Maintenance cost
F = Fuel and lubrication cost
TAC = Total annualized cost

TABLE 8-13. COST OF ALTERNATIVE NO_x CONTROLS FOR NATURAL GAS ENGINES FOR OIL AND GAS TRANSPORT

NO_x Control % Reduction		Cost Component[a] $/hp-hr	Retard (R) $/hp-hr	%Chg	Mnfd Cooling (M) $/hp-hr	%Chg	External EGR $/hp-hr	%Chg	Derate (D) $/hp-hr	%Chg	Air-to-Fuel (A) $/hp-hr	%Chg	R+M+A $/hp-hr	%Chg
20%	Low	AIC	0.00375	0	0.00381	1.5	0.00394	5	0.00426	14	0.00375	0		
		M	0.003	0	0.0031	3	0.0054	80	0.00341	14	0.0031	3		
		F	0.01556	1	0.01540	0	0.01540	0	0.01570	2	0.01540	0		
		TAC	0.02231	.7	0.02231	.7	0.02474	11.7	0.02337	5.5	0.02225	.5		
	High	AIC	0.00375	0					0.00577	54	0.00375	0		
		M	0.003	0					0.00462	54	0.0031	3		
		F	0.0160	4					0.01632	6	0.01570	2		
		TAC	0.02275	2.7					0.02671	20.6	0.02255	1.8		
40%	Low	AIC	0.00375	0					0.00426	14	0.00375	0	0.00381	1.5
		M	0.003	0					0.00341	14	0.0031	3	0.0032	6
		F	0.01570	2					0.01570	2	0.01570	2	0.01648	7
		TAC	0.02245	1.4					0.02337	5.5	0.02255	1.8	0.02349	6
	High	AIC							0.0075	100				
		M							0.0060	100				
		F							0.01910	24				
		TAC							0.03260	47				
60%	Low	AIC							0.00469	25	0.00375	0	0.00381	1.5
		M							0.00375	25	0.0031	3	0.0032	6
		F							0.01570	2	0.01570	2	0.01648	7
		TAC							0.02414	9	0.02255	1.8	0.02349	6
	High	AIC							0.00625	66	0.00375	0		
		M							0.005	66	0.0031	3		
		F							0.01878	22	0.01638	5		
		TAC							0.03003	36	0.02303	4.0		

[a]AIC = Annualized initial cost
M = Maintenance cost
F = Fuel and lubrication cost
TAC = Total annualized cost

TABLE 8-14. COST OF ALTERNATIVE NO_x CONTROLS FOR NATURAL GAS ENGINES FOR OIL AND GAS PRODUCTION

NO_x Control % Reduction		Cost Component[a] $/hp-hr	Retard (R) $/hp-hr	%Chg	Mnfd Cooling (M) $/hp-hr	%Chg	External EGR $/hp-hr	%Chg	Derate (D) $/hp-hr	%Chg	Air-to-Fuel (A) $/hp-hr	%Chg	R+M+A $/hp-hr	%Chg
20%	Low	AIC	0.00125	0	0.00127	1.5	0.00131	5	0.00142	14	0.00125	0		
		M	0.003	0	0.0031	3	0.0054	80	0.00341	14	0.0031	3		
		F	0.01778	1	0.01760	0	0.01760	0	0.01812	3	0.01760	0		
		TAC	0.02203	.8	0.02197	.5	0.02431	11.3	0.02295	5	0.02195	.5		
	High	AIC	0.00125	0							0.00125	0		
		M	0.003	0							0.0031	3		
		F	0.01830	4							0.01796	2		
		TAC	0.02255	3.2							0.02231	2.1		
40%	Low	AIC	0.00125	0					0.00156	25	0.00125	0	0.00127	1.5
		M	0.003	0					0.00375	25	0.0031	3	0.0032	6
		F	0.01796	2					0.01796	2	0.01796	2	0.01884	7
		TAC	0.02221	1.6					0.02327	6.5	0.02231	2.1	0.02331	6.7
	High	AIC							0.00156	25				
		M							0.00375	25				
		F							0.01830	4				
		TAC							0.02361	8.1				
60%	Low	AIC							0.00167	33	0.00125	0	0.00127	1.5
		M							0.004	33	0.0031	3	0.0032	6
		F							0.01830	4	0.01796	2	0.01884	7
		TAC							0.02397	9.7	0.02231	2.1	0.02331	6.7
	High	AIC							0.00167	33	0.00125	0		
		M							0.004	33	0.0031	3		
		F							0.01866	6	0.01848	5		
		TAC							0.02433	11.4	0.02283	4.5		

[a]AIC = Annualized initial cost
M = Maintenance cost
F = Fuel and lubrication cost
TAC = Total annualized cost

TABLE 8-15. SUMMARY OF LARGE-BORE ENGINE NO_x CONTROL COST PENALTIES (AS A PERCENTAGE OF UNCONTROLLED TESTS) BY END USE

	20% REDUCTION			40% REDUCTION			60% REDUCTION		
FUEL/APPLICATION	CONTROL[a]	AVERAGE	RANGE	CONTROL[a]	AVERAGE	RANGE	CONTROL[a]	AVERAGE	RANGE
Diesel/Electric Generation	R,D,E, A,RM, RMA	7	0-31	R,D, RA, AM	13	3-40	R,RA	16	14-18
	Excl. D	4	0-8	Excl. D	4	3-6			
	D only		9-31	D only		37-40			
Dual-Fuel Electric Generation	R,M,E, D,A	6	1-14	R,M,D,A RM	7	2-30	R,D,RA	14	5-33
	Excl. D,E	3	1-6	Excl. D	4	2-5	Excl. D	5	5-6
	D only		3-14	D only		13-30	D only		33
Natural Gas/Oil and Gas Transmission	R,M,E D,A	6	1-21	R,D,A RMA	9	1-47	D,A, RMA	10	2-36
	Excl. D,E	1	1-3	Excl. D	3	1-6	Excl. D	4	2-6
	D only		6-21	D Only		6-47	D only		9-36
Natural Gas/Oil and Gas Production	R,M E,D,A	4	1-11	R,D,A RMA	4	2-8	D,A RMA	4	2-11
	Excl. D,E	1	1-3	Excl. D	4	2-7	Excl. D	5	2-7
	D only		5	D only		7-8	D only		10-11

TABLE 8-16. RANGE OF COST PENALTIES (AS A PERCENTAGE OF UNCONTROLLED COSTS) FOR MANUFACTURERS' AVERAGE MODELS

TYPE OF ENGINE	INDUSTRY AVERAGE REDUCTION[a]	MANUFACTURER								MAXIMUM RANGE
		Colt	DeLaval	Ing-Rand	Cooper	Superior	Waukesha	Caterpillar	GM/EMD	
Gas	0%	0%	1-3%	1-3%	0%	1-3%	0%	1-3%		0-3%
	20%	0%	2-7%	2-7%	1-3%	2-7%	1-3%	1-3%		0-7%
	40%	1-3%	2-7%	2-7%	2-7%	2-7%	2-7%	2-7%		1-7%
	60%	2-7%	2-7%	2-7%		2-7%	2-7%	2-7%		2-7%
Dual-Fuel	0%	1-6%	0%	NA	1-6%	1-6%	NA	NA	NA	0-6%
	20%	2-5%	0%		1-6%	1-6%				0-6%
	40%	5-6%	0%		2-5%	2-5%				0-6%
	60%	5-6%	1-6%		5-6%	5-6%				1-6%
Diesel	0%	0%	0%	NA	0-8%	0%	NA	NA	0-8%	0-8%
	20%	0-8%	0-8%		3-6%	0%			3-6%	0-8%
	40%	3-6%	0-8%		3-6%	0-8%			14-18%	0-18%
	60%	14-18%	14-18%		14-18%	3-6%			14-18%	3-18%

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[a]Since average uncontrolled NO_x emission levels for each manufacturer vary, cost penalty ranges for a particular NO_x reduction level and fuel type will vary among manufacturers. Moreover, costs are incurred by some manufacturers at 0% reduction since average uncontrolled NO_x emissions from their engines are greater than industry average uncontrolled NO_x emissions.

NA = Not applicable.

cost penalty ranges among manufacturers at the 40- and 60-percent reduction levels; however, the variation within a cost penalty range is large enough (e.g., 2 to 7 percent) for cost differentials to exist among manufacturers. That is, two manufacturers could be in the 2- to 7-percent cost penalty range and one could incur a 2-percent penalty while the other incurred a 7-percent penalty. (The potential impacts of these differentials are discussed in Section 8.4.1.)

This observation also holds for the dual-fuel and diesel categories. The results for the diesel category indicate that Superior Division of Cooper has a cost advantage. However, Superior diesels are smaller, and in general, serve smaller power applications than Colt, DeLaval, or larger Cooper engines. Futhermore, the data are based on results from only one diesel engine model; therefore, the magnitude of this penalty may not be representative of penalties for all of these engines at this level of reduction. The data from Table 8-16 is analyzed in detail in Section 8.4.

8.2.2 Engine Manufacturers

Manufacturers of stationary reciprocating IC engines will incur additional costs due to the proposed standards of performance. As discussed in Section 6.3, these costs are a result of one or more of the following activities that may be needed to manufacture engines which meet standards of performance:

- Extended testing to verify the effectiveness of a particular control approach
- Development and application of NO_x controls to existing engine designs

- Engineering, tooling, and pattern costs for the redesign of an engine family

Costs related to these actions have been estimated for the control techniques summarized in Section 6.3 (technically viable approaches to meet proposed standards of performance) and are shown on Table 8-17[60,61]. These estimates are representative of the costs that manufacturers would incur to adapt each of the NO_x control systems to an engine family (i.e., group of engines with same air and fuel charging system and combustion chamber geometry). These figures include costs to test engines for durability and to retool their production facilities where necessary, but do not include costs to purchase or manufacture components placed on the engine. These latter costs are included in the user-oriented cost analyses of Section 8.2.1, which considered primarily additional hardware costs in the initial price. The table also gives estimated times to implement the various control technologies. It should be noted that these costs will double if a manufacturer is required to meet emission standards for two types of fuel (e.g., diesel and dual-fuel).

In general, manufacturers believe their present overhead budgets are sufficient for the development of the controls shown on Table 8-17, with the possible exception of EGR and combustion chamber modifications which will require considerably more development over a longer time. As shown in Section 4.3.1, all of the manufacturers have established baseline emissions for most of their engines. They believe that controls such as retard, air-to-fuel, manifold air cooling, derating, and combinations of these approaches would be relatively simple to implement, although some development time would be required to optimize a particular approach and

TABLE 8-17. ESTIMATED COSTS FOR ENGINE MANUFACTURERS TO DEVELOP NO_x CONTROLS, (BASED ON REFERENCES 60, 61)

CONTROL	DEVELOPMENT TESTS[a]		EXTENDED TESTS[b] (DURABILITY)		ESTIMATED TOTAL COST[c], $	TOTAL DEVELOPMENT TIME[d], MONTHS
	TIME, HR	COST, $	TIME, HR	COST, $		
Retard, R	200	25,000	2,000	100,000	125,000	15
Air-To-Fuel Change, A	200	25,000	2,000	100,000	125,000	15
Manifold Air Temperature Reduction, M	400	50,000	2,000	100,000	150,000	15
Derate, D	200	25,000	0	0	25,000	9
R + M	300	40,000	2,000	100,000	140,000	15
R + M + A	400	50,000	2,000	100,000	150,000	15
External Exhaust[e] Gas Recirculation, EGR	2,500	300,000	12,000	450,000	750,000	35
Combustion Chamber Redesign[e]	10,500	1,260,000	16,000	560,000	1,820,000	69

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[a]This is an estimate of exploratory and development time to establish operation and application data.

[b]This estimate assumes that one technician is in attendance full-time during a test of a 2000-hp engine.

[c]This includes research and development costs, durability tests, and retooling costs. Total cost estimates apply to one engine model family.

[d]From Table 6-5.

[e]Estimates for development time and costs include engineering and redesign of engine components.

establish its durability. Since several manufacturers have less experience in emission control research than others, the costs and times shown in Table 8-17 for these techniques have been estimated conservatively, taking into account the variation in emission control experience among manufacturers.

As discussed in Section 4.4, modifications of engine operating conditions, such as retard or air-to-fuel changes, may necessitate modifications of materials used for exhaust values and turbochargers, if exhaust temperatures greater than 1200°F (present material limits) are experienced. However, temperature data submitted with the emission data of Appendix C do not indicate excessive temperature will be encountered for the levels of retard and air-to-fuel changes reported.

Research and development of NO_x emission control techniques that require more extensive development and/or redesign (e.g., EGR or combustion chamber changes) are difficult to quantify. They will be determined to a large extent by a particular manufacturer's experience with emission controls, the uncontrolled emission levels of his engines, and the response of a particular engine to the control technique. Manufacturers have indicated that the time required to incorporate major engine design changes range typically from 3 to 5 years, but may extend to 10 years in some cases[62,63]. This time includes initial design, endurance testing (including 1 to 2 years operation in a real application, but under close monitoring by the manufacturer), and tooling-up (9 to 12 months). It is unclear to what extent the costs for these activities would be added to present R&D expenditures or absorbed into the existing budgets, thereby displacing R&D that would have been undertaken in the absence of emission standards.

These issues will be addressed further in Section 8.4 which discusses the economic impact of both users and manufacturers of IC engines subject to standards of performance.

8.2.3 Emerging Controls

In this subsection, the costs to control NO_x emissions from large-bore engines using exhaust gas treatment, combustion chamber modifications, or water induction are estimated. None of these systems has been used on a large-bore engine for any length of time; hence they cannot be considered for immediate application. At the same time they are not dependent upon any technological breakthroughs and should be available for use within 6 years, given appropriate priorities in the R&D budgets of the engine manufacturers.

Exhaust Gas Treatment: Ammonia/Catalyst System

Even though no engine manufacturer has reported on the application of NO_x reduction catalysts to large-bore engine exhausts, at least one source considers the reduction of NO_x by ammonia injection over a precious metal (e.g., platinum) catalyst as a promising control technique of the future (see Section 4.4.9)[64]. An estimate of the cost of this technique is presented in order to provide a comparison with the costs presented in Section 8.2.1 for the other NO_x controls.

The above-mentioned source reports that approximately 2 cubic feet of honeycomb catalyst (platinum-based) would be required for a 1000-hp engine to ensure proper operation of the system. The cost of the catalyst was estimated at $1500/cubic foot (in 1973). Assuming that the engine costs $150/hp and that the cost of the catalyst accounts for about onehalf the cost of the whole system (container, substrate, and catalyst), the capital investment for this control system represents approximately 4 percent of the engine purchase price. By comparison, catalyst systems for passenger automobiles represent approximately 3 to 5 percent of the purchase price of the automobile ($150 catalyst for a $3000 to $5000 automobile). If, however, this cost is expressed as a percent of the automobile's engine cost ($300 to $500), then the cost of the catalyst system is 30 to 50 percent of the initial price.

The amount of ammonia required for an ammonia/catalyst NO_x reduction system will depend on the NO_x emission rate (g/hp-hr). Based on uncontrolled NO_x emission rates of 9 to 22 g/hp-hr, as reported in Chapters 3 and 4, and the cost of $150/ton for the ammonia, the cost impact of injecting ammonia is approximately 5 to 15 percent of the total annual operating costs ($/hp-hr) for natural gas engines (see Table 8-8)[3/]. When this operating cost is combined with the capital cost of the catalytic system discussed above, the total cost increase is about 25 percent. Therefore, in continuous service applications this system is expensive compared to control techniques such as retard or air-to-fuel changes. However, the cost effectiveness ($ per mass NO_x removal) of an ammonia /catalyst NO_x reduction system could be quite low if the system is as effective on the exhaust from an IC engine as it is on the tail gas from nitric acid production plants. Nitrogen oxide reductions of approximately 90 percent have been reported in such cases, but the exhaust contained

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[3/] This cost approximation is based on a stoichiometric ratio of ammonia and nitrogen dioxide. On this basis 0.6 g NH_3 will reduce 1 g NO or 0.7 g NH_3 will reduce 1 g NO_2.

less than 5-percent oxygen[65]. Large-bore reciprocating engine exhaust contains considerably more oxygen (e.g., about 15 percent for gas engines); hence NO_x reduction may be less.

It is also important to note that the consumption of ammonia can be expressed as a quantity of fuel since natural gas is generally used to produce ammonia. Assuming a conservative NO_x emission rate of 20 g/hp-hr, and engine heat rate of 7500 Btu/hp-hr, a heating value of 21,800 Btu/lb for natural gas, and a requirement for approximately 900 lbs of gas per ton of ammonia produced[66], then the ammonia necessary for the catalytic reduction has the same effect on the supply of natural gas as a 2-percent increase in fuel consumption. Additional fuel is required to operate the plant which produces the ammonia.

Combustion Chamber Modifications

Section 4.4 described several chamber designs that have been shown to produce relatively low NO_x emissions from truck-size engines. There seems to be no technological reason why these designs cannot be adapted to larger engines (careful engineering analysis and design would be required to make the transition). Moreover, it was noted in Section 4.4 that a variable throat precombustion chamber design had been adapted to a large-bore engine in a laboratory. Therefore, an estimate of the costs associated with such a change is presented.

It is difficult to estimate the cost of designing a new, major change to an engine. One large-bore manufacturer estimates that a combustion chamber redesign would require 4 to 5-1/2 years to complete depending on the engine design (2- or 4-stroke cycle in this case). This redesign could affect pistons, cylinder heads and liners, injection components, and valves and would require an additional 12-month endurance testing before the final design could be released for production. This manufacturer would not need to expand his facilities for such a redesign program; nevertheless, he estimates the R&D expenditure would be in addition to normal development work and on the order of 1-1/2 times their typical development costs.

The estimate to be presented here comes from private contacts with manufacturers of truck-size engines who have considered the advisability of converting their direct-injection engines to precombustion chambers. They estimate an approximate development cost of $0.5 million, and note that this figure would be higher if their staff had not already developed familiarity with precombustion chambers through previous experiences. The estimate is based also on the experience of Teledyne Continental who reported a $3-million development and retooling cost for a gasoline engine with a new chamber and ignition system design to replace an existing production model[67]. This engine is rated at less than 100 horsepower, and several tens of thousands are produced each year (14,700 alone for stationary applications in 1974). Teledyne Continental's expenditure probably represents an upper bound for the costs that a large-bore engine manufacturer might face; his R&D costs might be more, but retooling expenses should be significantly less.

Based on this information, we estimate that it would cost a manufacturer of large-bore engines no more than $2 million to convert his units to precombustion chambers or squish lips. If one assumes that the average manufacturer in this group sells 50 engines a year, that the average rating of these engines is 1200 hp, that the cost of $150/hp applies, and that the manufacturer should be able to recover such an investment in

5 years, then he would have to increase the sales price of his engines by nearly 5 percent.

Presumably fuel consumption in these redesigned engines could also be 5 to 8 percent higher than it is for current models, just as in some precombustion chamber truck-size engines relative to their closest open-chamber equivalents. In that case, the economic impact from a standard that could be met only by such a redesign would be about 5 to 8 percent of the uncontrolled total annual costs for engines used in continuous service, depending on fuel penalty.

Water Induction

Research has indicated that the induction of water into the engine in quantities equivalent to the mass of fuel consumed can be effective in reducing NO_x emissions[68,69]. Reductions of approximately 60 percent in NO_x have been demonstrated on several gaseous fueled engines, using water to fuel mass flow ratios (lb water/lb fuel) of nearly one. In general, no increase in fuel consumption occurred (see Chapter 4 and Appendix C). However, this research indicated that serious maintenance and durability problems are associated with water induction, and therefore, this control technique has been omitted from the cost analysis of currently available techniques (Section 8.2.1).

Since this technology, however, could become available in the future after further testing with water treatment, different allowances in the water injectors, exhaust valves, etc., costs are estimated below for this potential technology.

Testing has shown that the water must be deionized prior to induction to remove minerals which would otherwise deposit in the engine (e.g., on the intake and exhaust valves) and adversely affect performance[70].

For a 1000-hp engine, approximately 1 gallon per min- ute would be required to obtain a water/fuel ratio of 1. Deionized water could be supplied in bulk with an appropriately sized storage facility at a price of $15/1000 gallons, excluding the initial price of the storage facility(71). Based on the information supplied in Table 8-8, such a system would cause the total annual cost (including water treatment and disposal, storage, and delivery system) for a 1000-hp gas or dual-fuel engine used in continuous service (8000 hr/yr) to increase about 8 percent, assuming no additional maintenance. Total annual costs, however, would increase approximately 25 percent if one made the reasonable assumption that engine maintenance requirements would be doubled (cleaning flow passages, dewatering or replacing lubricant, etc.). Corresponding increases for a similarly sized diesel-fueled engine would be approximately one-half as much, since diesel fuel costs about 2.5 times more than natural gas.

If the water is deionized at the engine location, the water cost will be approximately $50/1000 gallons for a system that supplies 1 gallon per minute(72). Total annual costs for a 1000-hp engine in continuous service fueled with natural gas would increase approximately 15 percent for no engine maintenance increase and 85 percent assuming engine maintenance costs doubled.

A larger engine, e.g., 6000-hp, would require a proportionately greater water rate to maintain a water/fuel ratio of one. A reverse osmosis water treatment system would be better suited for this higher volume application ($\approx$5 gallons per minute). Based on a $50,000 investment for this system and a raw water cost of $0.5/1000 gallons, the total nnual costs for a 6000-hp gas-fueled engine in continuous duty

(8000 hr/yr) would increase approximately 10 percent assuming no increase in engine maintenance, and 35 percent assuming maintenance charges doubled.

Summary of Emerging Control Techniques

The costs associated with an exhaust gas treatment system (ammonia) and with combustion chamber modifications are comparable to those for derating and EGR (see Table 8-15). Water induction control costs appear to be generally higher than for most control techniques summarized in Table 8-15, especially if deionized water is not readily available in bulk, and if maintenance is significantly increased.

8.2.4 Fuel Pretreatment

Desulfurization

Sulfur oxides arise from the nearly quantitative combustion of sulfur in the fuel. The fuels traditionally burned in reciprocating engines (i.e., gas and distillate oil) are low in sulfur, nitrogen, and ash. According to a recent survey, over 50 percent of all distillate contains less than 0.3 percent sulfur, and the average nitrogen content is about 0.03 percent[(73)].

As explained in Section 4.4.13 of this report, large-bore diesel engines are occasionally equipped to burn crude or residual fuel oils. These generally contain higher levels of sulfur than the more commonly used distillate fuels.[4/] Therefore, engines fired with the heavier high-sulfur fuels may incur increased control costs above those outlined in Section 8.2.1 for NO_x control alone. The purpose of this section of the report is to determine the cost of possible standards for the user who burns residual oil.

[4/] The sulfur content of fuel oils, in percent, is roughly comparable to the pounds of SO generated per million Btu heat input per hour. For example, 0.3 percent S results in about 0.3 pounds SO_2 per million Btu.

Currently, desulfurization of the lower grade fuels appears to be the preferred route to compliance with SO_2 emission standards.[5/] Desulfurization of residual fuel oils is widely used. Given that the cost of producing low-sulfur residual fuel oil depends on the specific characteristics of the crude oil used, the extent of desulfurization required, and many other variables, it is reasonable to establish a range of incremental desulfurization costs as follows[(74)]:

Desired Sulfur Level (Percent)	Desulfurization Cost ($/bbl)	Incremental cost[a] ($/bbl)	($/MBtu)[b]
1.0	1.10 to 1.50	0	0
0.8	1.25 to 1.80	+0.15 to 0.30	0.04
0.5	1.45 to 2.00	+0.35 to 0.50	0.07
0.3	1.60 to 2.20	+0.50 to 0.70	0.10

[a]Referenced to 1 percent sulfur level

[b]The heat content assumed in converting $/bbl to $/MBtu is 145,000 Btu per gallon of fuel oil. Also, values shown for $/MBtu are average values.

In the spring of 1975, residual oil with about 1-percent sulfur content cost $2.15/MBtu[(75)]. Hence, the cost to comply with a strict standard of 0.3 percent sulfur is equivalent to a 4.6-percent increase in fuel price. Since fuel costs account for about 75 percent of the total annual cost of operating an uncontrolled diesel-fueled engine in continuous duty (see Figure 8-9), this degree of desulfurization would result in

[5/]Since desulfurization is a purposeful system for fuel cleaning, it complies with the 1977 amendments to Section 111 of the Clean Air Act which requires the use of continuous technological systems of emission reduction.

a 3.5-percent increase in total fuel costs. Comparable increases for 0.5- and 0.8-percent sulfur (over 1 percent) are 3.2 and 1.9 percent, respectively.

Denitrification

While SO_2 in the reciprocating engine exhaust originates exclusively from the fuel, NO_x arises from thermal fixation of nitrogen in the air and from partial oxidation of nitrogen in the fuel. The control methods evaluated in Section 8.2.1 were devised only for thermal NO_x and have been tested with the traditional clean fuels (natural gas and distillate oil), where nearly all the NO_x generated is thermal. The possible use of heavier fuels suggests that fuel nitrogen may someday become a problem.

Thus, the currently available technology for control of NO_x from fuel nitrogen is, like that for control of SO_x, modification of the fuel. But whereas the desulfurization of residual oil is practiced deliberately, denitrification is practiced almost inadvertently. Some nitrogen is removed as a byproduct of desulfurization. The fraction removed is consistently less than that of sulfur but is rarely monitored. Nevertheless, nitrogen removal occurs at no cost above that for sulfur removal. The fuel is not sold under a nitrogen specification, and indeed the refiners have resisted (successfully, in times of fuel shortages) such a specification. Moreover, desulfurization competes with other refining processes for the limited supply of hydrogen. New developments in desulfurization catalysts have the incentive of reduced hydrogen consumption, but the newer catalysts remove less nitrogen. For the time being, then, the owner of an affected facility cannot buy low-nitrogen fuel by specification as he buys low-sulfur fuel. Low-nitrogen fuel can be used to help reduce

NO_x emissions but cannot be used in lieu of applying control techniques to the engines themselves to meet the standard because the standard(s) will be based on test data from installations burning the traditional clean fuels.

A standard of performance for NO_x which failed to recognize the special problem of fuel nitrogen would create a bias against the burning of residual fuels. One manufacturer indicated crude or residual oil is used in place of distillate where a long-term commitment for the heavy oil is at a price lower than distillate. This spokesman pointed out that since diesel fuel is regulated but not crude, the price of crude is not necessarily lower than distillate. In fact, crude oil must be significantly lower than No. 2 oil to justify the increased capital and maintenance costs for heavy fuel handling[76]. Furthermore, the lack of information regarding fuel-bound nitrogen formation and removal precludes a more comprehensive discussion. Therefore, since the proposed standards for diesel and dual-fuel engines will be based on emissions data obtained when using No. 2 oil, compliance with the standards may also require operation with No. 2 oil.

8.2.5 Modified Facilities

As discussed in Chapter 5, a user usually does not make physical or operational changes to an existing engine installation which would increase its NO_x emission rate. However, if he did, he would be required to conform to a standard of performance for new sources. Therefore, we will briefly consider the potential cost impacts of such a change.

Essentially the user contemplating a modification has two alternatives:

1. Make the modification, including use of the most practical available control technology (see Chapter 5) that prevents the emissions from increasing as a result of the modifications
2. Buy a new engine, or alternative power source, which satisfies the new requirement for which the modification was intended. If a new engine were purchased, the appropriate standard of performance would apply.

Normally a user would contemplate a modification for one of the following two reasons:

1. To increase the power output of his engine
2. To install newly designed parts, such as injectors or pistons, in place of the old ones during an overhaul

For example, a user might wish to install a new injector that the manufacturer designed to reduce smoke or fuel consumption. Other changes, as discussed in Chapter 5, could include alterations of the cylinder head, piston, valve or porting configuration, and manifolds.

If these changes resulted in greater NO_x emissions, the user would probably rely on the control techniques described in Chapter 6 to bring the modified engine within standards of performance. The cost impact would depend on the initial emission level and the NO_x emission level after modification. If the level after a modification was in the same range as those from new, uncontrolled units, the cost increases would also be similar to those presented in Section 8.2.1. (Derating is excluded as a possible control strategy since power requirements at existing facilities are fixed.)

At present there is insufficient data to judge the response of older engines to NO_x control techniques. Some older engines are likely to have emissions lower than a standard of performance for new sources, and emissions after modification could also be less. In other cases, this might not be so. Therefore, it is not possible to state quantitatively the economic impact for users who make a modification to their engine and are then required to meet a standard of performance.

When faced with the need to meet a standard as a result of an intended modification, an owner or operator would normally weigh the cost impact of this approach against that of replacing his existing facility with a new one. This new engine would, of course, meet the standard as well as satisfy his new need. The cost of a major overhaul is probably a reasonable estimate of the maximum price of a modification-plus-alteration to bring the engine into compliance with a standard of performance for new sources. For a large-bore, low- or medium-speed reciprocating engine, this cost is typically less than one-third (see Chapter 5) of the purchase price of the engine.[6/] Therefore, to be competitive, an alternative engine or power source would need to approximate this cost, taking into account both initial and operating costs. Thus, it is unlikely that the user would substitute a different engine (to comply with performance standards) rather than apply control technology to his existing engine.

[6/] A spokesman for one engine manufacturer indicated that practically all the development of design changes for new engines occurred in-house with the manufacturer incurring about 90 percent of the cost for endurance testing of the design change. Thus, end user-evaluation of design changes are rare, and hence, those costs are not included in this estimate.

8.2.6 Reconstructed Facilities

In large-bore, lower medium-speed engines the main housing, or structure, is never replaced during the engine's life, but at some time or other almost every component may be renewed. In general, the various parts are replaced at different times, as they wear out or break, but not at the same time (except for parts replaced during routine maintenance and overhaul). As noted in Chapter 5, overhauls are performed routinely throughout an engine's life and, therefore, should not be considered a reconstruction even though substantial portions of the engine are replaced (generally with parts identical to those originally installed). Therefore, since reconstruction within the meaning of 40 CFR 60.15 is not expected to occur, there is no need for estimating the cost impact of standards on reconstructions.

Industry spokesmen have expressed concern that a standard of performance might deter the replacement of older engines with newer, more efficient ones[78]. It does not seem likely, however, that the potential cost increases due to a standard would affect that decision. In fact, if one accepts an industry estimate that new engines consume about 75 percent as much fuel as older ones[79], then one can show that it is more cost effective to purchase such a new, efficient engine (i.e., one with a fuel consumption rate of 7500 Btu/hp-hr) for continuous duty than to simply maintain the old one. This is true even if the new engine is burdened with a 5-percent initial and 80-percent maintenance cost increase (e.g., with EGR) to represent the maximum cost penalty expected from controls, if it is assumed that the old engine is completely amortized, and if the same maintenance costs are assigned to the old engine as to an uncontrolled new unit. In fact, the difference in favor of the purchase is about 9 percent on an annualized basis.

8.3 OTHER COST CONSIDERATIONS

This section identifies any costs incurred by large-bore reciprocating engine users as a result of environmental regulations other than standards of performance for air pollution. Such regulatory requirements might concern solid waste disposal, water pollution control, or noise control. The purpose of this section is to identify incremental costs imposed by these regulatory requirements that may in some way limit the ability of the user to bear the cost of control techniques presented in Section 8.2.

Stationary reciprocating engines do not cause solid waste disposal or water pollution problems. Used lubricating oil is not considered a solid waste because it is either sold to an oil recycler or burned as fuel in a boiler. The only conceivable source of solid wastes or contaminated water from the operation of these engines might arise from water purification and demineralization for a water induction control system. These wastes, however, are currently hypothetical since such systems do not now exist; they may be used in the future if water induction is developed as an emission control technique. Treatment costs to prepare water for use in engine jacket and aftercooler cooling systems are presently accounted for in maintenance charges for these engines, and hence, have been included in the analysis presented in Section 8.2.1.

Similarly, no noise regulations are presently in effect specifically for large-bore reciprocating engines. These engines are typically installed in remote locations (e.g., gas pipelines) or separate buildings (e.g., electric utilities and standby service) where remote control of the engine or process reduces noise exposure. In addition, mufflers are used to reduce noise. However, one manufacturer of large-bore engines has reported that complex noise control systems could be cost-prohibitive to an industry whose manufacturers only sell a few hundred units per year and who typically have limited staff and facilities for noise control research [80]. This source reports, nevertheless, that manufacturers are beginning to incorporate noise control into their research and design programs.

End-users, on the other hand, have been faced with Occupational Safety and Health Act (OSHA) regulations limiting worker exposure to noise levels and EPA regulations for the protection of communities from annoyance. One source reports that noise control for engines in the 800- to 2000-hp range can cost as much as $10,000 to $30,000. [81] The level of effort to meet OSHA requirements is often unclear. For example, simple, relatively cheap devices such as earmuffs and earplugs can be used as a last resort when other methods of noise control prove technically unfeasible. However, the definition of technical feasibility is uncertain, and depends on the circumstances of each particular application.

In conclusion, there are no other regulatory requirements that, at present, will limit stationary reciprocating engine user's ability to absorb incremental costs as a result of standards of performance for air pollution.

8.4 ECONOMIC IMPACT

This section analyzes the economic impacts of alternative standards of performance for NO_x emissions from large stationary reciprocating internal combustion engines on engine manufacturers (Section 8.4.1), gas and electricity prices (Section 8.4.2), employment (Section 8.4.3), and foreign trade (Section 8.4.4). These impacts have been evaluated for alternative standards of 20, 40, and 60 percent below sales-weighted average emissions of uncontrolled gas, dual-fuel, and diesel engines. The extent of the impact for each alternative, assuming retard, air-to-fuel change, or manifold temperature reduction techniques are used to achieve compliance, is summarized in Section 8.4.5 and in Table 8-18.[7/] The following is a brief description of the results of the economic impact analysis.

The capital budget requirements for testing engine models are an estimated $5 million for a 60 percent alternative. These expenditures will be made over a two-year period and could be financed internally by engine manufacturers from profits on internal combustion engine sales. No firm is expected to lose more than seven percent of its sales to competitors. Gas turbine sales will not make additional inroads into sales of reciprocating engines with the possible exception of diesel engines used for electricity generation. The total U.S. electric bill would increase by 0.3 percent when controls are applied to all engines. This level would not be reached until all engines are replaced (full phase-in would take about 30 years). Localities using internal combustion engines exclusively to generate

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[7/] Other techniques-derate, combustion chamber modification, and exhaust gas recirculation -- are treated separately in this section. This is done since there is little likelihood they would be employed to meet these alternative standards. In addition, their wide range of possible penalties and applications preclude meaningful analysis.

TABLE 8-18. SUMMARY OF ECONOMIC IMPACTS

Impact	Alternative NO_x Standards		
	60%	40%	20%
Impact on Manufacturers (Section 8.4.1)			
Capital Budget Requirements	$5 million over two years; able to generate internally from profits.	$4.5 million	$4.1 million
Intra-Industry Competition 5% @ 60 6% @ 20-40	Maximum sales loss unlikely to exceed 5% of ICE sales for any firm.	6% max. loss	6% max. loss
Competition from Gas Turbines	No sales losses likely, except for diesel engines (where data are sketchy).	Possible sales loss for one diesel mfg.	No losses.
Impact on Product Prices and Users (Section 8.4.2)			
Electricity Prices	U.S. electric bill up 0.3% after full phase-in (in localities using only ICEs) could face a 9% max. increase.	U.S. bill up 0.1%; localities up 3% max.	U.S. bill up 0.1%. Localities up 3% max.
Gas Prices	Delivered gas prices up 0.4% after full phase-in (in 30 years).	Increase of 0.3%	Increase of 0.1%.
Impact on Employment (Section 8.4.3)	Little impact expected.	Same.	Same.
Impact on Foreign Trade (Section 8.4.4)	Engine sales unaffected. U.S. oil imports up 0.6%, all imports up 0.1% after full phase-in.	U.S. oil imports up 0.4%.	U.S. oil imports up 0.2%.

electric power, however, could face a maximum increase of nine percent. Delivered gas prices will increase by 0.4 percent when controls are fully implemented. No loss in jobs will take place nationwide. Local changes will be minor because sales shifts among manufacturers will not be large. U.S. oil imports will increase by 0.6 percent when controls are fully phased-in. Total imports of goods and services will increase by slightly more than 0.1 percent.

40 Percent Alternative

The impacts would be similar to those above, but somewhat less in the cases of capital budget requirements, product price increases, and import increases. Capital budget requirements would be $4.5 million because of the need to test fewer models; this is $0.4 million less than for a 60 percent standard. ElectroMotive diesel engines would still be vulnerable to gas turbine competition. The increase in the total U.S. electric bill would be 0.1 percent. The maximum increase for localities would be three percent. Gas prices would increase 0.3 percent. Oil imports would rise by 0.4 percent and total imports by slightly less than 0.1 percent.

20 Percent Alternative

Capital budget requirements would be $4.1 million. The possibility of any sales losses to turbine manufacturers would be remote. The total U.S. electric bill would increase by 0.1 percent, and the maximum increase for localities would be three percent. Gas prices would increase 0.1 percent. Oil imports would increase by 0.2 percent and total imports by less than 0.1 percent.

Comparing the impacts among the various alternatives -- 60, 40, and 20 percent -- there is no evidence that any of the alternatives would cause an extraordinary impact. The following sections present a detailed discussion of the economic impacts that were considered.

8.4.1 Impact on Manufacturers

The most direct economic effect of alternative standards of performance is on the manufacturers of large stationary reciprocating internal combustion engines. This impact involves three areas -- capital budget requirements, intra-industry competition, and competition with gas turbines.

8.4.1.1 Capital Budget Requirements

To implement NO_x reductions for their engines, manufacturers will require capital outlays to develop and test engine control techniques and to maintain production of existing model engines under emissions regulations. The size of these outlays will depend primarily on the number of models each firm would need to test, the extent of further testing required, the fuel prices paid during testing, and whether or not adequate laboratory facilities were in place. The ability to finance the outlays will depend upon the profitability of the engine line and the ease with which the initial costs could be absorbed by the companies' current capital resources.

A precise estimate of the outlays cannot be determined without a detailed evaluation of specific control levels by each company. Certain models have uncontrolled emissions that already meet the 20 and 40 percent alternatives, although not the 60 percent alternative. These are shown in Table 8-19. Models that already meet the alternative levels without controls would not require testing. Other models with high uncontrolled emissions may be such a minor part of a company's business that the company would drop them rather than test them with controls. The data as collected, however, do not reveal the importance of individual models to the companies. Furthermore, it is also possible that certain models would not have to be tested because of the test results gained from other models. The amount of

TABLE 8-19. THE CUMULATIVE NUMBER OF MODELS CURRENTLY ACHIEVING VARIOUS ALTERNATIVE STANDARDS

Alternative Met (Reduction from average uncontrolled emissions)	Diesel	Dual Fuel	Gas	Total
60%	0	0	0	0
40%	3	1	1	5
20%	6	1	2	9
Uncontrolled	11	5	23	39

Notes: Totals include only engine models for which data are available. This includes 39 out of a total of 49 models.

previous testing and the stringency of the standard may also determine the outlay required.

As discussed in Section 8.2.2, two phases of testing are required by the manufacturer to establish that an engine can meet an emission standard: 1) development and 2) extended durability tests. The tests used as a data base for this study will have met the development needs of manufacturers in many cases. However, where models must be controlled more than 40 percent, additional development tests may be needed. Such tests would cost about $25,000 per model tested. Ingersoll-Rand and Alco may need to establish in-house testing laboratories at an additional cost of $50,000 for test instrumentation for each firm.

After development testing, engine models must undergo extended tests to prove the durability of emissions reductions and operations. These tests would be about three times more costly than the development tests. As noted in Section 8.2.2, the entire testing process can take 15-18 months. Several models can be tested concurrently, though several development tests might be needed before a manufacturer can select the best control technique. Overall, development and extended durability testing would cost about $100,000 per engine model. This estimate is based upon confidential correspondence from two manufacturers; it could overstate the actual costs for the 20- and 40-percent alternative standards (which would need fewer development tests).

The total number of internal combustion engine models produced by each firm and the estimated capital budget requirement for testing to satisfy standards of performance are shown in Table 8-20. The total industry bill, including the cost of establishing new laboratories at two firms, would be approximately $5,000,000 for a 60 percent alternative (requiring testing of up to 49 models). The bill would be about $500,000 less ($4.5 million) for the 40 percent alternative, and about $900,000 less ($4.1 million) for the 20 percent alternative, since fewer models would need testing (see Table 8-19).

The capital test requirements would be regarded as an added expense for the manufacturers. The expense would be measured against the profitability of each engine line. The larger the profits, the smaller the burden of the expense. Manufacturers would either absorb the added expense by reducing profits, pass it on to customers in the form of higher prices, or drop the engine line as an uneconomic part of the business.

TABLE 8-20. ESTIMATED CAPITAL BUDGET REQUIREMENTS TO MEET NO_x STANDARDS OF PERFORMANCE

Manufacturer	Number of Models[a]	Capital Budget Requirements for NO_x Standards of Performance[b]
Colt	7	$ 700,000
DeLaval	5	500,000
Caterpillar	2	200,000
Waukesha	4	400,000
ElectroMotive	2	200,000
Cooper Industries (Cooper & Superior)	24	2,400,000
Ingersoll-Rand	4	450,000
Alco	1	150,000
All Firms	49	$5,000,000

[a]An engine model is defined by a set of fuel, air charging, number of strokes, and displacement per cylinder (bore and stroke) parameters.

[b]Based on an average test cost of $100,000 per engine model. Ingersoll-Rand and Alco will have additional expenses of $50,000 each to establish test laboratories.

A major question is whether the internal combustion engine manufacturers will have the financial resources from which to fund the initial capital requirements. They can be funded either externally by increasing debt or internally by using current capital budgets or allocating funds from the capital budgets of other divisions in the parent company. Price increases could be used in addition to these financing techniques to recover the expenses over a number of years. If manufacturers were to seek to recover the annualized cost of test outlays over a five-year period, on average they would have to raise engine prices only one percent (ranging among manufacturers from 0.4 to 2.1 percent).

Although any combination of the above financing techniques could be used, engine divisions are likely to operate from their own internal resources. Unlike investments in new products or plants, the capital test outlays would represent investments in established lines of business and thus, would entail much lower risk. Moreover, these divisions are small parts of their parent companies, as Table 8-5 in Section 8.1.2 shows. Therefore, raising debt or obtaining funds from other capital budgets would not be difficult for such an investment.

Although the precise capital budgets cannot be determined without a detailed evaluation of a specific control level by each company, as previously mentioned, the prospects for internal financing can be put in perspective by comparing capital budget requirements with the sales and profits of internal combustion engine operations. This can be done in a rough manner by comparing parent companies' profits as a percentage of sales (see Table 8-21) to their internal combustion engine divisions' additional capital budget requirements as a percentage of sales. The internal combustion engine divisions' test requirements as a percentage of sales cannot be shown in order to preserve the confidentiality of sales data disclosed by manufacturers. However, in no case did the percentage exceed five percent of sales or the ratio of the parent company's after-tax profits to sales. This is true even in the case of Colt or ElectroMotive where parent company profits fell below five percent of sales during the 1975-1976 period.

TABLE 8-21. FINANCIAL RESOURCES

Consolidated Parent Firm of Engine Manufacturer	Profits as % of Sales 1976	1975
Ingersoll-Rand	5.6	7.0
General Motors (ElectroMotive)	6.2	3.5
Colt Industries	4.9	5.1
Caterpillar	7.6	8.0
Cooper Industries (Cooper & Superior)	7.5	6.5
Dresser (Waukesha)	7.0	6.2
TransAmerica (DeLaval)	a	a
General Electric	5.9	4.3
All Firms[b]	6.4%	5.8%

[a]TransAmerica is primarily a financial corporation whose sales are not easily compared with sales of products of manufacturing corporations.

[b]Average profit margin computed as a simple average for all firms for which data were available.

SOURCE: Securities and Exchange Commission Corporate 10-K reports and annual reports to stockholders.

Providing that the internal combustion engine part of the business has approximately the same profit margins based on sales as the parent companies, this indicates that in the case of each manufacturer, the additional capital budget could be financed with funds generated internally from domestic sales of large stationary reciprocating internal combustion engines. In addition, testing expenses would not be subject to taxes which would otherwise be applied if the firm earned profits of that amount. For example, if

$100,000 of expenses were incurred instead of realizing $100,000 of gross profit subject to the marginal federal corporate tax rate of 48 percent, the corporation would have $52,000 less cash flow and the U.S. Government would receive $48,000 less taxes. In effect, the expenditure would cost the corporation $52,000 rather than the nominal $100,000 if it were absorbed from profits and not passed on through price increases.

In the event standards were set that required exhaust gas recirculation or combustion chamber modification, the capital budget requirements would change. Based on confidential correspondence with manufacturers, it is estimated that test requirements for the industry would double -- to ten million dollars -- and the testing time required would double or triple -- to three to five years. Hence, although cost doubles, the time involved doubles or triples. This means that the annual requirement stays the same or decreases. This capital requirement would compete more for a company's overall resources because it is larger and more extended. If only one manufacturer had to incur this amount, it might mean less resources for normal product development or investment and thus some competitive disadvantage.

8.4.1.2 Intra-Industry Competition

Manufacturers would not have significant differential impacts for alternative standards that require spark retard, air-to-fuel changes, or manifold temperature reduction. If derate, exhaust gas recirculation, or combustion chamber modification were required, cost penalties among engines would be disparate and might cause competitive shifts in the sales shares of manufacturers.

To identify whether or not significant changes in sales would take place, the engine penalty data were analyzed in conjunction with confidential sales data for each manufacturer. Worst-case impacts were determined by looking at the maximum variation possible among engine penalties in a particular market. Where the range of penalties shown in Table 8-16 of Section 8.2.1.3 was small, such as in gas engines, one company would not have an advantage over another company. For instance, at the 40 percent alternative for gas engines it is possible that Waukesha could incur a seven percent penalty and Caterpillar a two percent penalty or vice versa, since both of them would incur cost penalties of from two to seven percent.[8/] The maximum differential cost penalty for these two competitors in the gas production market is then five percent (seven percent less two percent).

Cross-price elasticities were then considered using the above results. One spokesman estimated that, in one of their highly competitive markets, he would expect a 10 percent increase in price to lead to a 20 percent decrease in sales.[9/] Another spokesman, referring to the internal combustion engine market as a whole, estimated that a five percent increase in price would not have any noticeable effect on their sales, but that a 10 percent increase, even industry-wide, would lead to a 10 percent decrease in sales. At markups beyond 10 percent, we have no estimates of the price elasticities, but have assumed that every one percent increase in price would result in a two percent decrease in sales.

[8/] It should be noted that just because the data show that Caterpillar would have to reduce its emissions by an average of 46 percent versus 33 percent for Waukesha, it does not mean that the Waukesha penalty could not fall into the high end of the range and the Caterpillar penalty into the low end of the range.

[9/] This assumes sales are in terms of dollars rather than units. If sales were based on units, the impact on dollar sales would be less.

A third factor considered was the importance of each market to the companies' total internal combustion sales. If standby and export markets (which make up almost half of all large stationary reciprocating internal combustion engine sales) are exempt from standards of performance, this would leave manufacturers with a substantial part of their business unaffected. In addition, as described in Chapter 9.3, smaller bore engines will be exempt from proposed standards of performance. Therefore, only a portion of a manufacturers' engine sales will be affected by standards. Thus differential cost penalties arising from standards would lead to only limited impacts on sales shares.

In combining these factors in a hypothetical example, a manufacturer incurring a possible six percent penalty over his competitors would lose 12 percent of his sales in that market (assuming the worst-case cross-price elasticity), which might be 25 percent of his total sales to all markets -- hence, he would lose only three percent of his total sales. (It should be noted that these are large stationary reciprocating internal combustion engine sales, not total engine sales or parent corporation sales which would make this percentage much smaller.)

In addition, one manufacturer indicated that parts and services accounted for over 25 percent of his annual sales.[82] Since standards of performance would not affect the outstanding population of engines, parts, and services, revenues would provide a stabilizing factor for all manufacturers in the short run, though this would lessen over time.

In the following analysis of intra-industry competition for each of the major submarkets, sales losses of more than 10 percent in any market were used to identify significant effects. For most manufacturers, the potential sales loss was considerably less than 10 percent in most of the submarkets they participated. Moreover, these potential losses were constructed from an admittedly extreme set of assumptions concerning the penalty differential, cross-price elasticities, and cost pass-through. The exact percentage of potential sales loss that could occur under these conditions was withheld to protect the confidentiality of the data.

8.4.1.2.1 Electricity Generation

There are two markets to discuss in the area of electricity generation. The first is the dual fuel market supplied by Colt, DeLaval and Cooper/Superior. Based on uncontrolled emission data, DeLaval has a distinct advantage over Colt and Cooper/Superior at the 20, 40 and probably 60 percent alternative levels. The maximum differential impact would be six percent, but no manufacturer would lose 10 percent of its internal combustion engine sales at any of the three control levels.

The second market is the diesel fuel market supplied primarily by Colt, DeLaval, Cooper/Superior, and ElectroMotive. Here, a maximum differential impact of 18 percent is possible at the 40 percent level of control with ElectroMotive suffering the disadvantage. Nevertheless, ElectroMotive has substantial mobile engine sales for locomotives which would be unaffected by proposed standards. It is important to note that the 14-18 percent penalties shown in Table 8-16 are based on data from one engine model. Such limited test data do not necessarily reflect the range of penalties for stringent alternatives since not all engines were tested. Moreover, it is possible that some models might be able to attain low levels of emissions only through techniques like derate or combustion chamber modification at much higher penalties. These would be outside the range shown in the table. It is the likelihood of such additional penalties, rather than the data shown in the test sample, that lead to the possibility of significant differential impacts at stringent levels of performance standards. For these reasons, no firm conclusions can be drawn except that even with an 18 percent differential no manufacturer would lose 10 percent of its internal combustion engine sales.

8.4.1.2.2 Gas Production

Ingersoll-Rand, Cooper/Superior, Waukesha, Caterpillar, DeLaval and Colt sell internal combustion engines to the gas production market. As previously mentioned, the average cost penalties for manufacturers would range from one to seven percent -- a maximum differential of six percent. At worst, this would mean that the most any manufacturer would lose would be 12 percent of its sales in this market, but no manufacturer would lose 10 percent of its internal combustion engine sales for all markets at any of the three alternative levels.

8.4.1.2.3 Gas Transmission

Cooper, DeLaval, Ingersoll-Rand and Waukesha sell internal combustion engines to the gas transmission market. Because the engines are gas-fueled, cost penalties are similar to those in the gas production market, and no manufacturer would lose 10 percent of its internal combustion engine sales at any of the control levels.

8.4.1.2.4 Other Markets

All manufacturers have sales to other markets. These include gas-fueled, dual-fueled, and diesel engines. However, the applications involved are diverse and comprise what are actually many different segmented markets. It would not be accurate to characterize differential penalties across such diverse applications. As noted in subsection 8.4.1.2.3, gas-fueled engines have a low differential penalty and therefore, would not involve much change. Dual-fuel sales to other markets are too small to have a significant impact. Only Colt and ElectroMotive sell diesel engines to other markets. Again, it can be expected that the other markets for diesel engines include many diverse applications. For a 20 percent control alternative, the maximum differential penalty would be five percent. For 40 percent, the maximum average penalty differential increases to 15 percent. This still would not result in a 10 percent loss in internal combustion engines sales for either firm, even if their applications overlapped completely. For the 60 percent alternative, the maximum differential is only four percent for the two firms (but is based on limited data).

8.4.1.2.5 Standby, Export, and Small Engines

Standby and export sales of large stationary reciprocating internal combustion engines accounted for 44 percent of all sales of large stationary reciprocating internal combustion engines (by horsepower) in the years 1972-1976 for all the manufacturers. In addition, data on sales of stationary reciprocating internal combustion engines below the regulated size limits (see Chapter 9.3) were not available for this analysis. Assuming these applications are exempt from proposed standards of performance, possible percentage loss of sales for each manufacturer is reduced further. By focusing only on a small section of the NO_x emitting stationary reciprocating engine population (which nonetheless emits the bulk of NO_x from installed sources), the proposed standards of performance affect less than half of the total stationary reciprocating internal combustion engine sales of manufacturers.

8.4.1.2.6 Aggregate Impact on Manufacturers

Because of the broad range of most control penalties, it is not always clear whether the engine manufacturers will gain, lose, or stay even in a given market. This is especially true where combustion chamber modification, derate, or exhaust gas recirculation is involved. It is reasonable to assume that the disadvantages some manufacturers may face in one market may be at least partly offset by advantages they gain in another market. This is highly dependent on the manufacturers' product mix and the cross-price elasticities of each market. It has also been shown in the previous subsections that the industry as a whole is buffered by substantial sales on nonregulated internal combustion engines. The market segmentation within major markets and the importance of other application factors would also soften any impacts.

Of the seven manufacturers studied for intra-industry impacts (Caterpillar, Colt, Cooper/Superior, DeLaval, Electromotive Division of General Motors, Ingersoll-Rand, and Waukesha), only Colt and ElectroMotive appeared to have a clear disadvantage in more than one market at certain control levels. Partly because Colt's sales are concentrated in the highly competitive electricity generation equipment market, and partly because their nonregulated sales are not nearly as significant as ElectroMotive's, Colt could potentially suffer the most significant intra-industry impact.

Assuming that Colt, the most vulnerable manufacturer, were to suffer the most extreme differential in each of the markets in which they participate, and assuming the worst possible cross-price elasticities, Colt would suffer a loss in sales of about six percent.[10/]

[10/] Across-the-board standards of 20, 40, and 60 percent could result in six, six, and five percent sales losses, respectively, by Colt.

The conclusion that intra-industry impacts would be sustainable and not cause any major dislocations within the indsutry holds for the degree of control for which the test data represent comprehensive ranges. At stringent levels for the standards (e.g., 60% reduction from uncontrolled data), the possibility arises that some models might require expensive control techniques that would widen the ranges and differentials. Only further testing can ascertain how significant this would be. It is also possible that even at the most stringent levels of control, the differential impact might be insignificant.

8.4.1.3 Competition From Gas Turbines

To assess the possible inroads turbines might make in the reciprocating engine market as a result of performance standards on new IC engines, market structure, cost, and other factors must be considered. The three major markets for turbines and reciprocating engines (electricity generation, oil and gas production, and oil and gas transport) are segmented into several submarkets in which factors such as size, weight, durability, reliability, vibration, and ability to handle load variations often dictate the choice of engine. Previous experience with the vendor, reputation, service, and familiarity with existing equipment are usually important considerations in the replacement market.

Turbines do not compete with reciprocating engines based on annualized costs alone, due to their higher operating (fuel) costs, at least not in the normal operating range of reciprocating engines which is 6,000 to 8,000 horus per year. As Table 8-12 shows, reciprocating engines controlled to the

60 percent level are less expensive to own than even uncontrolled turbines, with one possible exception in the electricity generation market [11/]

Table 8-22 also shows that for all the other markets, even the maximum penalty which could be imposed on internal combustion engines would not bring the cost of owning internal combustion engines up to that of turbines.

Proposed NO_x NSPS standards for gas turbines used in electricity generation are estimated to increase their cost by about two percent, and for oil and gas transportation and production applications by one to four percent. Consideration of the proposed NO_x NSPS will not affect the conclusions which can be drawn from this table.

TABLE 8-22. TURBINE VERSUS RECIPROCATING INTERNAL COMBUSTION ENGINES BREAKEVEN ANALYSIS

Application	Fuel	Maximum Reciprocating Engine Cost Penalty (as % of total annualized costs) NO_x Reduction Alternative 20%	40%	60%	Breakeven[a] for 6000 to 8000 hr/yr
Electricity Generation	dual fuel	6%	6%	6%	35-39%
	diesel	8%	18%	18%	12-14%
Oil and Gas Transportation	gas	7%	7%	7%	13-14%
Oil and Gas Production	gas	7%	7%	7%	25-30%

[a]This represents the total annualized cost penalty which would have to be experienced by reciprocating internal combustion engines before they would equal the cost of uncontrolled turbines.

[11/]New Source Performance Standards were proposed for stationary gas turbines in the 3 October 1977 Federal Register, Volume 42, Number 191.

8.4.1.3.1 Electricity Generation

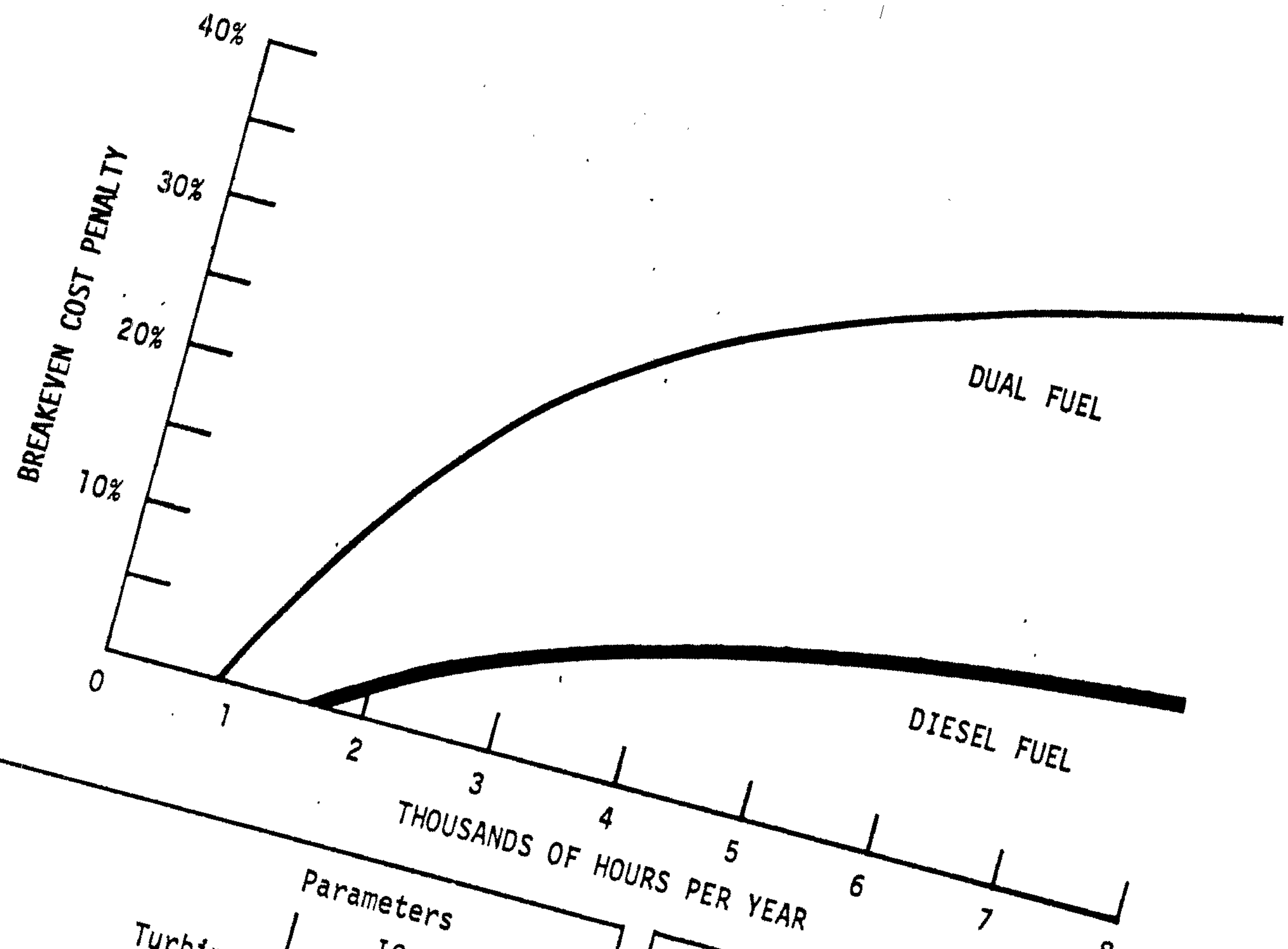
Data shown in Table 8-22 of the cost analysis section indicate that cost penalties of 14-18 percent could be incurred by some diesel engine manufacturers due to controls. One manufacturer, Electromotive, would incur that penalty even at a 40 percent level of NO_x reduction. For all other manufacturers, turbines would still cost more.

Table 8-22 shows that a 12-14 percent cost penalty would bring diesel reciprocating engines used in electricity generation up to the point where they would have no cost advantage over uncontrolled turbines. Since turbines would only incur about a two percent penalty for the proposed NO_x new source performance standard controls,[83] it appears that they would become competitive with diesel reciprocating engines. This conclusion, however, is based on only one data point used to calculate the 14-18 percent diesel engine penalty and, as such, should not be used as a decision criteria, considering that some uncertainty exists at the greater control alternatives (60 and 40 percent) for which there are test data. Furthermore, it is unlikely that turbines would replace diesel engines in plants using banks of smaller reciprocating engines, unless the entire bank were replaced with one turbine.

At the 20 percent alternative, turbines do not compete with the internal combustion engines on a cost basis. As load factors decrease, however, turbines become increasingly competitive due to their lower capital costs as shown in Figure 8-11. The formulas and methodology used to produce this and other graphs illustrating the breakeven points in Table 8-22 are shown separately on Table 8-23.

8.4.1.3.2 Oil and Gas Transportation

Although the reciprocating gas engines in gas transportation lose a large portion of their cost advantage over turbines in the high end of the



Parameters

	Turbine-Diesel	IC Engines: Dual Fuel	IC Engines: Diesel
CRF (%)	.2	.2	.2
K ($/kW)	120	200	200
OM ($/kW)	$.05K_t$	.004 ($/kWh)	
P ($/MMBtu)	2.5	2	2.5
E $\left(\frac{MMBtu}{kWh}\right)$	.0132	.0087	.0093

Breakeven Factors = X

Hr/Yr	Dual Fuel	Diesel
1,000	1.026	.937
2,000	1.159	1.016
3,000	1.238	1.060
4,000	1.290	1.087
5,000	1.327	1.106
6,000	1.354	1.120
7,000	1.375	1.131
8,000	1.392	1.140

Dual Fuel:

$$X = \frac{\frac{.25(120)}{Hrs/Yr} + 2.5(.0132)}{\frac{.2(200)}{Hrs/Yr} + .004 + 2(.0087)}$$

Diesel:

$$X = \frac{\frac{.25(120)}{Hrs/Yr} + 2.5(.0132)}{\frac{.2(200)}{Hrs/Yr} + .004 + 2.5(.0093)}$$

Figure 8-11. Internal combustion engines vs. turbines in electricity generation applications.

TABLE 8-23. METHODOLOGY FOR CALCULATING THE BREAKEVEN CURVES FOR FIGURES 8-10, 8-11, AND 8-12

$$\text{Cost (in mills/kWh)} = \frac{(CRF)K}{Hr/Yr} + OM + P(E)$$

The breakeven factor for the cost penalty to reciprocating engines (X) occurs where:

$$\frac{(CRF)K_t}{Hr/Yr} + OM_t + P(E_t) = X\left[\frac{(CRF)K_r}{Hr/Yr} + OM_r + P(E_r)\right]$$

Solving for the breakeven factor:

$$X = \frac{\frac{(CRF)K_t}{Hr/Yr} + OM_t + P(E_t)}{\frac{(CRF)K_r}{Hr/Yr} + OM_r + P(E_r)}$$

The percentage breakeven cost penalty = 100(X-1), where:

X = breakeven factor

CRF = capital recovery factor (i.e., .2 = 20%)[a]

K = installed cost of engine or turbine ($/kW)

OM = operating and maintenance cost ($/kWh)

P = price of fuel (i.e., distillate $2.50/MMBtu; gas $2.00/MMBtu)

E = heat rate efficiency in MMBtu/kWh

t = turbines

r = large reciprocating internal combustion engines

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[a]Assuming a 20-year accounting life, 10 percent interest rate, and four percent fixed capital charge (includes property taxes, insurance, administration and overhead).

penalty range presented in Table 8-22, they are generally used in different applications, and substitution would not be imminent, even at the breakeven point of total annualized costs.

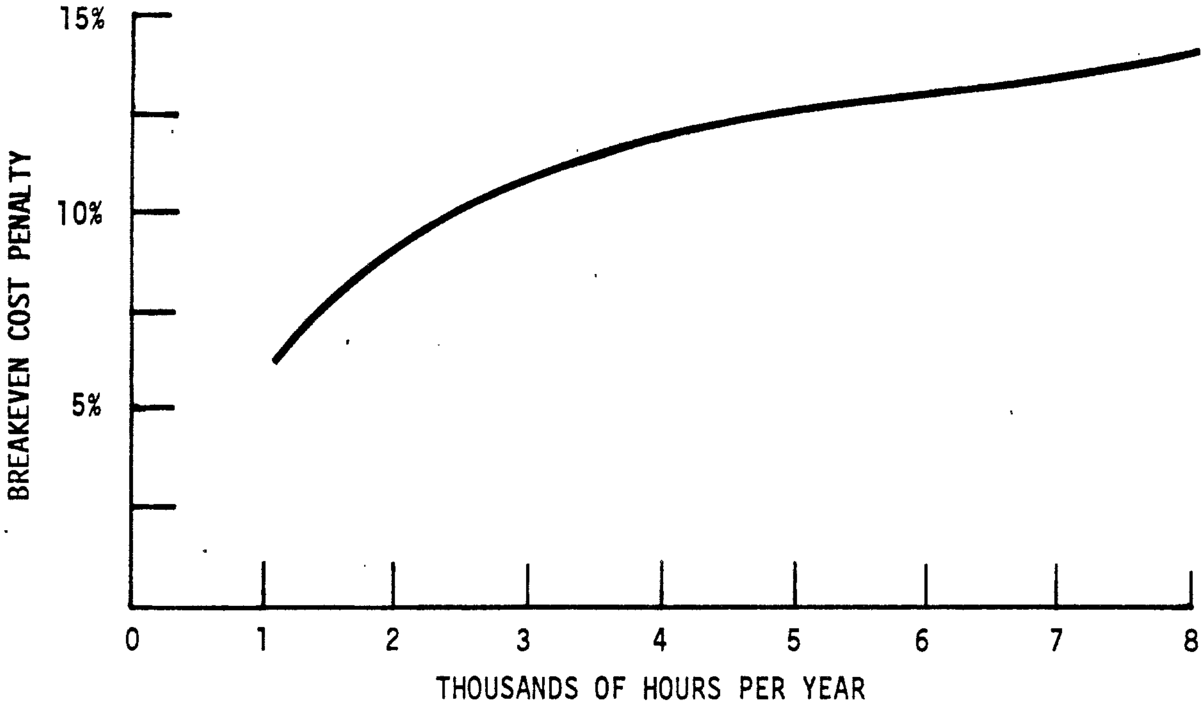
Gas turbines in gas compression uses serve primarily mainline transmission roles and provide power in new installations. Gas turbines are larger, so one turbine would provide the same power as several internal combustion engines. When existing reciprocating engine compression installations are expanded, however, reciprocating engines are purchased unless the old engines are scrapped. Moreover, turbines power centrifugal compressor equipment, while internal combustion engines power reciprocating compressor equipment. Hence, existing stations would not mix or change motive forms unless they also changed their compressor equipment.

Furthermore, turbines are not as well suited for gathering, storage, or pressurization where the flow is highly variable and the discreate power requirements are in the range that internal combustion engines offer. Thus, engines are typically located at the distribution end of pipelines, whereas turbines are located on the main trunk lines.

In addition, high load factors (characteristic of compressor applications) favor the more efficient internal combustion engines, especially as gas prices rise. Figure 8-12 shows that internal combustion engines maintain this advantage, even at load factors as low as 1,000 hours per year.

8.4.1.3.3 Oil and Gas Production

Turbines are clearly uncompetitive on purely a cost basis in this market. They are less efficient and much more expensive than internal combustion engines and are primarily used on offshore rigs where lighter and more portable equipment is a necessity. Uncontrolled turbines used for extraction



Parameters

	Turbine-Gas	IC Engine-Gas
CRF (%)	.2	.2
K ($/kW)	160	200
OM ($/kW)	$.05K_t$	.004 ($/kWh)
P ($/MMBtu)	2.00	2.00
E ($\frac{MMBtu}{kWh}$)	.0132	.0093

Breakeven Factors = X

Hrs/Yr	Gas IC Engines
1,000	1.061
2,000	1.089
3,000	1.106
4,000	1.117
5,000	1.124
6,000	1.130
7,000	1.134
8,000	1.138

$$X = \frac{\frac{.25(160)}{Hrs/Yr} + 2(.0132)}{\frac{.2(200)}{Hrs/Yr} + .044 + 2(.0093)} = \frac{\frac{40}{Hrs/Yr} + .0264}{\frac{40}{Hrs/Yr} + .0226}$$

Figure 8-12. Internal combustion engines vs. turbines in oil and gas transportation applications.

purposes are at least 25 percent more expensive to own than internal combustion engines, as Figure 8-13 shows.

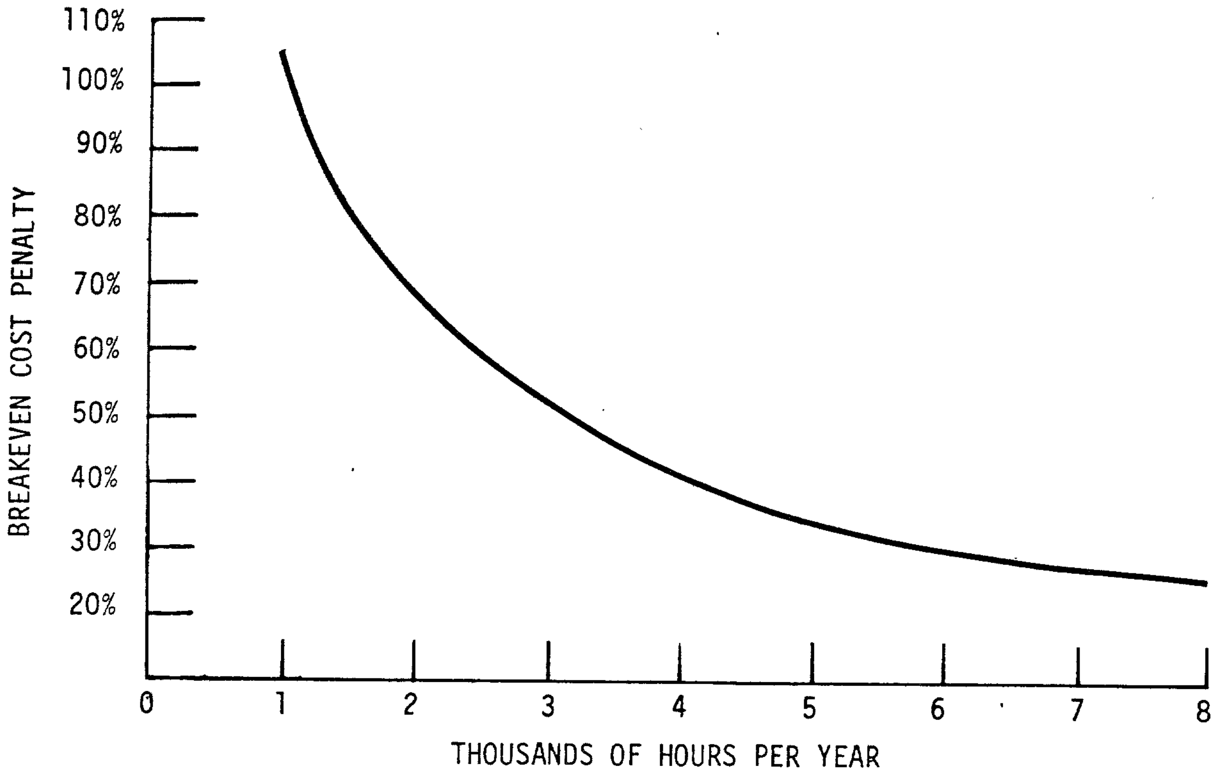
8.4.2 Impact on Product Prices

NO_x standards will affect product prices primarily for electricity and natural gas. However, cost increases will be insignificant, even if emissions standards are set at 60 percent average reductions. The analysis is explained below in terms of 20, 40, and 60 percent NO_x reduction alternatives. Because there are three kinds of engines (diesel, dual fuel, and gas) and three alternative levels (20, 40, and 60 percent) for emissions standards, the number of possible options for standards would be too large to cover in a readily comprehended manner. To simplify the presentation, this analysis considers across-the-board standards for all the fuels together.

8.4.2.1 Cost Pass-Through

When the demand for a manufacturer's goods is inelastic (i.e., insensitive to price changes), added costs are likely to be transferred to the consumer. This cost pass-through occurs where the manufacturer's product is viewed as a necessity by the consumer with few, if any, substitutes available. The extent of pass-through, then, depends on many factors in addition to the unique qualities of the product -- the price elasticity of demand for the industry as a whole (determined in part by other demands which are indirectly related) and the cross-price elasticities of the products within the same industry. It is assumed that since manufacturers produce reciprocating engines for essential applications in specialized market, cost increases would be passed through to the consumer.

Section 8.4.1.3 demonstrated that the internal combustion engine industry does not now face competition from gas turbines based on cost factors



Parameters

	Turbine-Gas	IC Engine-Gas
CFR (%)	.2	.2
K ($/kW)	210	67
OM ($/kW)	$.05K_t$	.004
P ($/MMBtu)	2.00	2.00
E $\left(\frac{\text{MMBtu}}{\text{kWh}}\right)$	.0136	.01067

Breakeven Factors = X

Hrs/Yr	Gas IC Engines
1,000	2.057
2,000	1.668
3,000	1.500
4,000	1.406
5,000	1.345
6,000	1.304
7,000	1.273
8,000	1.250

$$X = \frac{\frac{.25(210)}{\text{Hrs/Yr}} + 2(.0136)}{\frac{.2(67)}{\text{Hrs/Yr}} + .004 + 2(.01067)} = \frac{\frac{52.5}{\text{Hrs/Yr}} + .0272}{\frac{13.4}{\text{Hrs/Yr}} + .02534}$$

Figure 8-13. Internal combustion engines vs. turbines in oil and gas production applications.

alone for either of the two main applications--electricity generation and gas compression during production and pipeline transmission--in which NO_x standards will cause cost penalties. In electric generation, it may be recalled, turbines are uneconomic for baseload use and for additions to plants already using banks of reciprocating engines. In gas compression, gas turbines are not suited to gathering applications (because of variable gas flow) and are not easily added to stations already using reciprocating engines.

Furthermore, the industry is segmented into many specialized markets and submarkets, as discussed in Section 8.1.3. Most internal combustion engines have carved out a niche in which they have few, if any, substitutes in the applications for which they are used.

At the same time, demand for engines would not likely fall significantly as a result of higher prices for engines in the range that the test data indicate would take place. The increase in some localities for electric rates would be, at its maximum, somewhat higher--nine percent--but is much less than recent increases from other causes, while past rate increases have not led to much decrease in demand for electricity (see subsection 8.4.2.2). Municipalities have the option of purchasing power from larger utilities, but tend to produce the bulk of their own needs and purchase only small amounts of power. (Frequently, these utilities sell power.) Furthermore, consumers would not consume appreciably less gas because of a 0.4 percent increase in delivered prices (see subsection 8.4.2.3).

With little decrease likely for overall engine demand and little competition from substitutes, manufacturers will likely pass through cost increases to consumers.

8.4.2.2 Electricity Generation

Reciprocating internal combustion engines are used to generate electricity on a continuous (baseload) basis for small municipalities. They account for only a small fraction of total electricity generation in the United States. There were 936 internal combustion plants (excluding gas turbines) at year-end 1975.(84) These had a total generating capacity of 5,021 megawatts--equal to one percent of the total U.S. electric generating capacity of 505,772 megawatts.(85) Therefore, the impact on electricity prices is best measured in two dimensions--local and weighted national impacts.

Although localities deriving all of their electricity from internal combustion are rare, and the chances of all of those engines being subject to NSPS are remote at least in the near future, an evaluation of this case was done to provide the maximum possible increase in electricity prices which could be experienced by any consumer. Based on a sample of ten utilities using internal combustion engines to generate at least 90 percent of their electricity sales, engine costs (engine price, maintenance, and fuel expenses) typically account for half the costs of delivered electricity to consumers.(86) Electricity distribution and general overhead costs account for the remainder and would be unaffected by NO_x standards. Therefore, an engine penalty from NO_x standards would be halved when applied to the price that consumers pay for electricity in these localities. Table 8-24 shows the inflationary impact on local electricity prices for various emissions standards.

The maximum impact is nine percent and takes place in the case of diesel engines at a 60 percent alternative (based on data from only one model). Recent sales of diesel and dual fuel engines to the electric

TABLE 8-24. MAXIMUM INFLATIONARY IMPACT ON LOCAL ELECTRICITY PRICES

	Alternative NO_x Reductions		
Engine type	20%	40%	60%
Diesel	3%	3%	9%
Dual Fuel	2%	3%	3%

generation market indicated that new sales were running approximately 50 percent diesel and 50 percent dual fuel.

In comparison, electric rates have increased far more than other factors. Since 1970 residential, commercial, and industrial electric rates have risen by five percent to 30 percent annually. This is shown in Table 8-25.

TABLE 8-25. HISTORICAL PERSPECTIVE ON ANNUAL INCREASES IN ELECTRICITY PRICES

Period	Residential 500 kWh	Commercial--30, kW, 6,000 kWh	Industrial--300 kW, 60,000 kWh
1970 to 1971	6.2%	5.5%	7.6%
1971 to 1972	7.6%	7.3%	8.5%
1972 to 1973	4.6%	4.9%	5.7%
1973 to 1974	12.4%	11.1%	15.6%
1974 to 1975	27.3%	24.8%	30.6%
1975 to 1976	7.2%	6.3%	6.5%
Range	4.6%-27.3%	4.9%-24.8%	5.7%-30.6%

SOURCE: Federal Power Commission, Typical Electric Bills, 1976.

Because internal combustion engines account for just a small fraction of all electricity generated nationwide (with the national electric bill from private utilities alone valued at $44.4 billion in 1976),[87] the NO_x emissions standards on new source reciprocating internal combustion engines would raise the national electric bill by just a fraction of a percent. If the standards had been fully implemented in 1976, the inflationary inpact on the national electric bill would have been just 0.1 percent in the case of 20 or 40 percent alternatives and 0.3 percent in the case of a 60 percent alternative. This is shown in Table 8-26.

TABLE 8-26. MAXIMUM INFLATIONARY IMPACT ON THE NATIONAL ELECTRIC BILL WITH FULL PHASE-IN

	Alternative NO_x Reductions		
Impact	20%	40%	60%
Increase	0.1%	0.1%	0.3%

In actuality, new source performance standards are phased-in only gradually. Penalties are not incurred until new controlled engines are purchased, while old uncontrolled engines are retired from service after a 30-year lifetime. Assuming new sales equal to three percent of the existing engine population and retirements also equal to three percent (in effect, a steady population as indicated by recent sales data), after five years, approximately 15 percent of all engines will be controlled and will incur penalties. The inflationary impact of the standards at that time is shown in Table 8-27. It ranges from 0.02 percent for a 20 percent standard to 0.04 percent for a 60 percent standard.

TABLE 8-27. INFLATIONARY IMPACT ON THE NATIONAL ELECTRIC BILL, AFTER FIVE YEARS

Impact	Alternative NO_x Reductions		
	20%	40%	60%
Increase	0.02%	0.02%	0.04%

8.4.2.3 Gas Production and Transmission

Reciprocating internal combustion engines are used to transport most of the gas consumed in the United States. Internal combustion engine costs account for only six percent of the delivered price of gas ($1.60 per Mcf in 1976),[88] though the percentage is somewhat higher for areas distant from producing states. The average cost penalties for gas engines (which account for nearly all recent sales to the reciprocating pipeline engine market) ranged from two percent at a 20 percent alternative to six percent at a 60 percent alternative. Table 8-28 shows the impact of these penalties on delivered gas prices.

TABLE 8-28. INFLATIONARY IMPACT ON DELIVERED GAS PRICES, AFTER FULL PHASE-IN

	Alternative NO_x Reductions		
Impact	20%	40%	60%
Increase	0.1%	0.3%	0.4%

The largest inflationary impact, at a 60 percent alternative, would involve a price increase of just 0.4 percent. (This was calculated as if all engines in use in 1976 had been controlled and incurred penalties.) By comparison, the national average delivered price of gas has risen by 103 percent in recent years--from \$.79 per Mcf in 1973 to \$1.60 per Mcf in 1976--[89] from other causes.

The increase in gas prices would not reach the above levels until all engines were controlled. With sales and retirement rates equal to those in the electric generation market (i.e., three percent annually), in five years controls would cover 15 percent of all engines. The inflationary impact at that time would be a 0.06 percent increase in the case of the most stringent standard (60 percent). This is shown in Table 8-29.

TABLE 8-29. INFLATIONARY IMPACT ON DELIVERED GAS PRICES, AFTER FIVE YEARS

	Alternative NO_x Reductions		
Impact	20%	40%	60%
Increase	0.02%	0.04%	0.06%

8.4.2.4 Impacts Over Five Years

Users of internal combustion engines will have to lay out additional capital expenditures to purchase more expensive engines (the engine purchase price component of the cost penalty from NO_x controls). In the case of internal combustion engines, however, the capital cost penalty is small. Most of the penalty comes from higher fuel or maintenance costs. A two percent engine price penalty can be expected on average for all alternative standards.[12] With annual industry domestic non-standby internal combustion engine sales of $96 million (projected to remain roughly constant), the additional capital cost for users would equal $1.9 million per year -- a total of $9.6 million on a cumulative basis over the first five years.

Total costs in the fifth year (including amortized capital costs, maintenance costs, and fuel costs) would range from $16 million for a 20 percent alternative to $26 million for 40 percent and $45 million for 60 percent.

In dollar terms, the impact of the standards is shown in Table 8-30 for all markets in the fifth year after the standards are implemented.

TABLE 8-30. COSTS OF VARIOUS ALTERNATIVE STANDARDS IN THE FIFTH YEAR (IN MILLION DOLLARS)

Application	Alternative NO_x Reductions 20%	40%	60%
Gas Production & Transmission	5.9	13.6	17.8
Electric Generation	7.9	8.9	19.9
Other Applications	2.2	3.4	7.1
All Applications	16.0	25.9	44.8

[12] Two percent reflects a one percent increase from pass-through of test costs and an average of one percent increase for use of manifold temperature reduction in some cases. (Manifold temperatures reduction would incur a price increase of two percent where used, but would probably be used less frequently than other techniques.)

8.4.3 Impact on Employment

Since NO_x standards will not cause significant changes in manufacturers' sales if retard, manifold temperature reduction, and air-to-fuel changes only are used, they will not cause significant impacts on employment.

Nationally, sales shifts among manufacturers will tend to balance out with no decrease in aggregate sales or employment in the industry. As noted in Section 8.4.4 (below), exports and imports of internal combustion engines will not likely experience any changes because of NO_x standards on engines used in the U.S. Therefore, few jobs would be lost to foreign firms. Moreover, because sales changes of greater than 10 percent are not expected (and most would be much less), the extent of local shifts will also be minor.

8.4.4 Impact on Foreign Trade

The foreign trade balance will not be significantly affected by NO_x standards. The amount of imported engines is not expected to change. Most internal combustion engine imports have been engines that are smaller than the minimum size to be controlled by the proposed standards. Department of Commerce data showed that the average value of imported diesel engines in 1973 was \$889 per unit.[90] This is far below the likely cost for a diesel engine of the size that would be controlled by the proposed new source performance standards since a typical 1,000 horsepower diesel engine would cost about \$150,000. In addition, imported engines would have to meet NO_x emissions standards. Because foreign firms would have smaller U.S. sales volumes over which to spread capital test requirements for NO_x reductions, the NO_x standards would actually tend to create a barrier to imports.

Proposed NO_x standards do not apply to engine exports. Control techniques like retard, air-to-fuel changes, manifold temperature reduction, and derate do not involve changes in mass production items. There would be no loss in scale economies to manufacturers if they had to produce controlled engines for domestic sales and uncontrolled engines for export sales. Moreover, even techniques like combustion chamber modification and exhaust gas recirculation would have little impact on exports, because of the specialty nature of the large engine industry, where even without controls, each engine is typically tailored to a specific customer's needs rather than just mass produced.

Fuel imports would be increased marginally by the fuel penalties involved in meeting NO_x standards. In the fifth year after standards take effect, 15 percent of all engines will be controlled. The additional fuel requirement (to be met by additional imports of oil) in that year would be 1.0 million barrels of oil for a 20 percent alternative, 1.5 million barrels for 40 percent, or 2.4 million barrels for 60 percent. This is shown in Table 8-31.

TABLE 8-31. ADDITIONAL FUEL NEEDS, IN THE FIFTH YEAR (MILLION BARRELS)

Engine Type	Alternative NO_x Reductions 20%	40%	60%
Gas	0.6	1.0	1.0
Diesel	0.3	0.4	1.4
Dual Fuel	0.1	0.2	0.1
All Engines	1.0	1.5	2.4

Measured against 1976 oil imports of 2,850 million barrels,[91] the increase in oil imports would be 0.04 percent for a 20 percent alternative, 0.05 percent for 40 percent, and 0.09 percent for 60 percent. Measured against 1976 imports of all goods and services of $160 billion and valued at an average of $12.10 per barrel,[92] the increase in U.S. imports would be 0.008 percent for a 20 percent alternative 0.011 percent for 40 percent, and 0.018 percent for 60 percent.

8.4.5 Summary of Economic Impact Analysis

With minor exceptions, there appears to be little difference among the impacts of a 60 percent, 40 percent, or 20 percent alternative. This is a qualified judgment based on the assumption that derating, exhaust gas recirculation, or combustion chamber modification will not be necessary in order to meet these alternatives.

Although aggregate price impacts on consumers vary directly with the level of control, even a 60 percent alternative would raise gas and electricity prices less than half a percent. On the local level, however, it is theoretically possible for a locality entirely dependent on new reciprocating internal combustion engines for generating its electricity to experience a nine percent increase in electricity prices at the 60 percent alternative. This is three times more than the increases for the 40 or 20 percent alternative. Such localities, however, would represent an extremely small part of the overall population.

Manufacturers would face only limited impacts. Capital test requirements would be within their ability to finance internally from profits, while the costs could be recovered through a one percent average price increase over a five-year period. Despite variations in cost penalties, no firm is likely to lose more than five to six percent of its sales (in all of their markets). Gas turbines may make inroads into certain manufacturers' sales for diesel engines only at a 40 or 60 percent alternative, but their cost advantage in the normal operating range of 6,000 to 8,000 hours per year would be slight. Employment, like sales, would experience little change. Imports and exports of internal combustion engines would also face little change. Oil imports would increase by only a fraction of a percent.

Several additional points can be noted. In summary, the full impact of the standards would not be markedly different for the 20, 40 and 60 percent alternatives. Second, based on conservative analytic techniques, the only possible impact of notable magnitude would be the rise in electric prices for isolated localities using all internal combustion engines. Third, full attainment of the impacts on users will not be realized until all engines are replaced by controlled engines incurring penalties -- a process that will take 30 years to complete.

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9. RATIONALE

9.1 SELECTION OF SOURCE FOR CONTROL

Previous investigators have concluded that stationary internal combustion (IC) engines are major contributors to nationwide emissions.[1,2,3] In particular, stationary IC engines are sources of NO_x, hydrocarbons (HC), particulates, sulfur dioxide (SO_x), and carbon monoxide (CO) emissions. NO_x emissions from IC engines, however, are of more concern than emissions of these other pollutants for two reasons. First, NO_x is the primary pollutant emitted by stationary engines. Second, EPA has assigned a high priority to the development of standards of performance limiting NO_x emissions. Assuming existing levels of emission controls, national NO_x emissions from stationary sources are projected to increase by more than 40 percent in the 1975-to-1990 period. Applying best technology to all sources would reduce this increase but would not prevent it from occurring. This unavoidable increase in NO_x emissions is attributable largely to the fact that current NO_x emission control techniques are based on combustion redesign. In addition, few NO_x emission control techniques can achieve large (i.e., in the range of 90 percent) reductions in NO_x emissions. Consequently, EPA has assigned a high priority to the development of standards of performance for major NO_x emission sources wherever significant reductions in NO_x can be achieved. Studies have shown that IC engines are significant contributors to total U.S. NO_x emissions from stationary sources. Figure 9-1[4] shows that internal combustion engines account for 16.4 percent of all stationary source NO_x emissions,

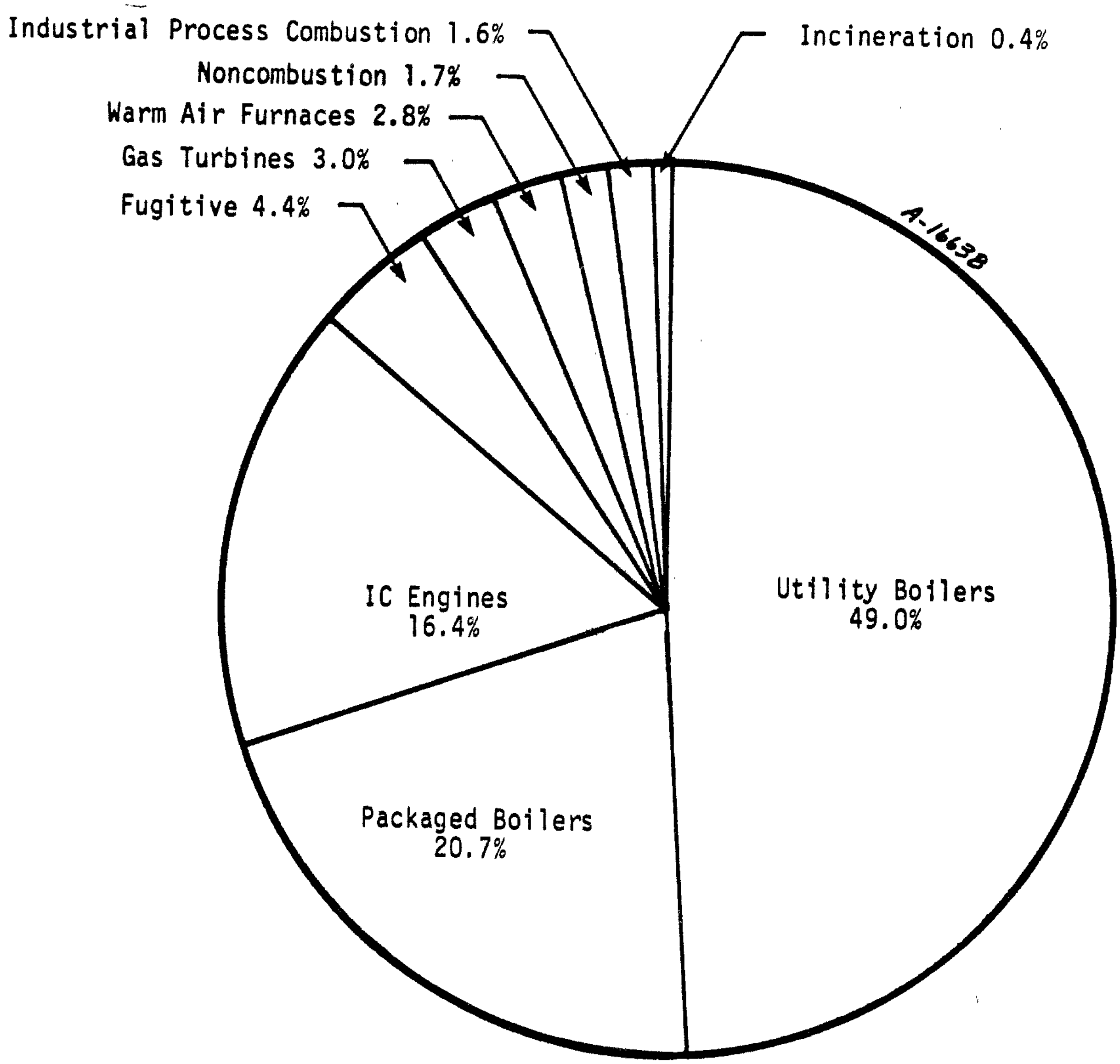

Figure 9-1. Distribution of stationary NO_x emissions for the year 1974 (Reference 4).

exceeded only by utility and packaged boilers.

An inventory of emissions from installed stationary engines was computed based on the information presented in summary form in Table 9-1.[5] As a group, stationary IC engines (based on 1975 data) currently account for 3 to 9 percent of the NO_x, carbon monoxide (CO), and hydrocarbons (HC) emitted from all sources, and 9 to 14 percent of those emitted from stationary sources. This table also shows the percentage contribution to nationwide totals from installed engines as a function of their size and the type of fuel they consume. Table 9-2[6] shows the emission factors used to generate Table 9-1. Annual production rates are estimated in Table 9-1 to indicate the potential number of sources that could be affected by New Source Performance Standards (NSPS).

Table 9-3[7] presents a clearer picture of the relationship between the number of potentially controllable sources and their contributions to the nationwide inventory from currently installed units.* This table also shows that numerous small engines (nearly 13 million units of 1- to 100-hp) are the most significant contributors of HC and CO emissions from IC engines. (Note that nearly 80 percent of the HC emissions from engines smaller than 350 CID/cyl are methane, a noncriteria pollutant.) Therefore, it can be concluded that NO_x emissions constitute the most significant pollutant emitted by stationary engines since three-quarters of these emissions are emitted by large-bore (greater than 350 CID/cyl) engines.

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*Table 9-3 includes a separate row of emission estimates for engines larger than 350-cubic-inch displacement per cylinder (CID/cyl). As is shown in Section 3, it is more meaningful to discuss the applications and emissions of large IC engines on the basis of displacement per cylinder rather than on horsepower.

TABLE 9-1. NATIONWIDE EMISSIONS FROM INSTALLED IC ENGINES (Percent of Total Emitted in U.S. Each Year)[a]

Fuel	hp Range	Annual Production, Units[b]	NO_x	CO	HC_T
Diesel	20 - 100	39,000	0.36	0.029	0.062
	101 - 500	14,000	0.55	0.45	0.095
	>500	3,400	0.48	0.016	0.033
	Subtotal	56,400	1.39	0.09	0.19
Natural Gas	<500	5,400	1.93	0.107	0.81
	>500	600	4.16	0.229	1.73
	Subtotal	6,000	6.10	0.336	2.54
Dual-Fuel		Included in Diesel	0.28	0.02	0.11
Gasoline	<15	12,600,000[c]	0.16	1.84	0.56
	15 - 99	85,000	0.31	0.81	0.29
	>100	10,000	0.11	0.31	0.10
	Subtotal	12,600,000 + 95,000	0.58	2.96	0.95
	Total	12,600,000 + 157,400			
Percent All Sources			8.4	3.4	3.8
Percent Stationary Sources			13.7	11.0	8.8
In Mass Units (10^6 metric tons/yr)			2.0	3.6	0.9

[a]Total U.S. emission from EPA Nationwide Air Pollutant Inventory for 1975(5)

[b]Based on estimates of average hp of engines used in each application

[c]Includes all engines in this size category (mobile and stationary). Listed separately in the totals because of the unique nature of this group

TABLE 9-2. EMISSIONS FACTORS FOR INVENTORY ON TABLE 1,[a] g/hp-hr (Reference 6)

Fuel		NO_x	CO	HC_T
Gasoline	>15 hp	8.85	102	8.38
	<15 hp	5.63	295	20.5
Diesel	>500 hp[b]	12.9	1.8	0.43
	<500 hp[c]	12.4	4.47	2.12
Natural gas		11.5	2.81	4.86
Dual-Fuel		8.2	2.0	3.1

[a]Emission factors for gasoline and diesel engines are modal averages; those for natural gas and dual-fuel are for rated conditions.

[b]Based on an average of rated condition levels from engines considered

[c]Weighted average of two- and four-stroke engines. Weighting factors = 2/3 for four-stroke and 1/3 for two-stroke

TABLE 9-3. EMISSIONS FROM IC ENGINES BY SIZE AND ANNUAL PRODUCTION[a]

Annual Production			Emissions from Installed Engines[b] (% U.S. Total)					
Size	Units/yr	Increment	NO_x	Increment	CO	Increment	HC_T	Increment
>350 CID/cyl[c]	1,600		4.83		0.26		1.86	
>500 hp	4,000	2,400	4.92	0.09	0.26	0.003	1.87	0.01
>100 hp	28,000	24,000	5.59	0.66	0.59	0.33	2.07	0.20
>15 hp	152,000	124,000	6.26	0.67	1.43	0.83	2.42	0.35
All	12,752,000	12,600,000	6.42	0.16	3.27	1.84	2.98	0.56
Total	(10^6 metric tons/year)		1.53		3.47		0.72	
All Sources	(10^6 metric tons/year)[d]		23.8		105.8		24.2	
Stationary Sources	(10^6 metric tons/year)[d]		14.5		32.6		10.4	

[a]Compiled from Table 9-1
[b]Excludes emissions from natural gas engines under 500 hp (insignificant future impact projected from new engines due to declining sales)
[c]Cubic Inch Displacement per cylinder. All gas and dual-fuel engines >500 hp are taken to be greater than 350 CID/cyl. Of the 3400 diesel units >500 hp, 1000 are assumed to be greater than 350 CID/cyl. These large bore diesels contribute 80 percent of the emissions from diesel units >500 hp.
[d]From EPA Nationwide Air Pollutant Inventory for 1975(7).

Other studies have investigated the emissions of various stationary sources to aid in establishing a priority for setting standards of performance. For example, the Research Corporation of New England determined the effect that standards of performance would have on nationwide emissions of particulates, NO_x, SO_x, HC, and CO from stationary sources.[8] As per EPA-450/3-78-019, "Priorities for New Source Performance Standards under the Clean Air Act Amendments of 1977," sources were ranked according to the impact, in tons per year, that standards promulgated in 1980 would have on emissions in 1990. This ranking placed spark ignition IC engines second and compression ignition IC engines third on a list of 32 stationary NO_x emission sources. Consequently, stationary IC engines have been selected for development of standards of performance.

In a subsequent study, Argonne National Laboratory used the results of the TRC study to develop a priority listing for setting NSPS.[9] In developing this list, source screening factors were used to aid in establishing these control priorities. Factors considered were:

- Type, cost, and availability of control technology
- Emission measurement methods and applicability
- Enforceability of regulations
- Source location and typical source size
- Energy impact
- Impact on scarce resources
- Other environmental media constraints

The study found that even with the application of maximum NSPS control efforts, a significant increase of more than 40 percent in NO_x emissions occurs in the 1975-to-1990 period. Furthermore, the study concluded that the control of internal combustion engines emissions is a matter of high priority.

Other factors favoring the control of IC engines are summarized briefly below:

- Control techniques for NO_x emissions have been shown to be effective and applicable to installed IC engines. These techniques can reduce NO_x emissions from 40 to 60 percent on the average (see Section 4.0).
- No federal, state or local NO_x standards exist (with the exception of Los Angeles and Chicago). Therefore, since engines are manufactured for a variety of dispersed applications, a single national standard is preferable.
- IC engines compete with gas turbines in certain applications. Since NSPS are currently being developed for gas turbines, the absence of standards for IC engines may result in a shift away from gas turbines to IC engines. This could cause greater NO_x emissions from both sources than if no standard were applied to gas turbines, since IC engines emit NO_x at greater rates than gas turbines.

Furthermore, as shown in Section 3.0, sales of large-bore engines, primarily for oil and gas exploration, have been substantial during the past five years, and are anticipated to continue and possibly increase. Stationary IC engines, therefore, are significant contributors to total nationwide emissions of NO_x. Consequently, based on all these factors, stationary IC engines have been selected for development of standards of performance.

9.2 SELECTION OF POLLUTANTS

Oxides of Nitrogen

Stationary engines emit the following pollutants: NO_x, CO, HC, particulates, and SO_x. As Table 9-3 indicates, the primary pollutant emitted by stationary engines is NO_x, accounting for over six percent (or 16 percent of all stationary sources) of the total U.S. inventory of NO_x emissions. This table also illustrates that large-bore engines emitted three-fourths of these NO_x emissions. It will be shown in Section 4.0 that the control technology exists to effectively reduce NO_x emissions from large-bore engines. Furthermore, NO_x emissions are projected to increase despite promulgation of all possible New Source Performance Standards. Therefore, NO_x emissions from stationary engines have been selected for control by means of NSPS.

Hydrocarbons and Carbon Monoxide

Table 9-3 also shows that stationary IC engines emit substantial quantities of CO and HC as well. Numerous small (1-100 hp) spark ignition engines, which are similar to automotive engines, account for about 20 percent of the uncontrolled HC emissions and about 80 percent of the uncontrolled CO emissions. However, as mentioned in Section 9.3, the large annual production of these small spark ignition engines (approximately 12.7 million) makes enforcement of a new source performance standard for this group difficult.

An additional factor in considering CO and HC control is that inherent engine characteristics result in a trade-off between NO_x control and control of CO and HC. A detailed discussion of the trade-off can be found in Section 9.4. In some cases, particularly naturally aspirated gas engines, the application of NO_x emission control techniques could cause increases in CO and HC emissions. This increase in CO and HC emissions is strictly a function of the engine operating position relative to stoichiometric conditions, not the NO_x control technique. Any increase in CO and HC emissions, however, represents an increase in unburned fuel and hence a loss in efficiency. Since IC engine manufacturers compete with one another on the basis of engine operating costs, which is primarily a function of engine operating efficiency, the marketplace will effectively ensure that CO and HC emissions are as low as possible following the application of NO_x control techniques. In addition, promulgation of CO and HC emissions standards of performance could, in effect, preclude significant NO_x control. CO emissions, which are primarily a function of oxygen availability and only secondarily of temperature, show a pronounced rise as the mixture becomes richer than stoichiometric, but little variation as it becomes leaner. Carbureted engines, however, which are beset by large variations in cylinder-to-cylinder air-to-fuel ratios, must operate near the stoichiometric ratio to ensure that no individual cylinder receives a charge which is too lean to ignite (i.e., exceeds the lean misfire limit). Consequently, increasing the air-to-fuel ratio to near stoichiometric to reduce the CO emissions increase has the effect of also limiting the NO_x emissions reduction.

These and other factors discussed in Section 9.3 led to the recommendation of a NO_x NSPS for large-bore engines but not for HC and CO emissions since:

- The IC engines which emit significant quantities of NO_x are, with some exceptions, low emitters of HC and CO
- Many of the NO_x reduction techniques discussed in Section 4.4 cause little or no increase in the already low HC and CO emissions rates from most large-bore engines
- Individual engines can cause violation of the National Ambient Air Quality Standards for HC only under worst-case atmospheric conditions, and then only very close to the source (less than 0.3 km)
- No controls for HC used in conjunction with NO_x controls have been demonstrated which reduce the already low nonmethane HC emissions from large-bore engines

Particulate

No standards of performance are recommended for either particulate emissions or visible emissions (plume opacity). This recommendation stems from the following considerations:

- Virtually no data are available on particulate emission rates from stationary engines because it is so difficult, expensive, and time-consuming to measure particulates, especially when done in strict compliance with EPA Method 5 sampling techniques
- It would be very expensive to enforce a standard on required measurements for particulates in compliance testing which would be in accordance with EPA Method 5
- It is believed that particulate emission from stationary engines are relatively unimportant because the plumes from most of these engines are not now visible

SO_x

Sulfur oxides (SO_x) emissions are strictly dependent upon the sulfur contained in the fuel. Thus, annual sulfur oxide emissions from an engine depend on the percent sulfur in the fuel and the fuel consumption of the engine during that year. Most engines burn low-sulfur fuels and will continue to do so since crude and residual fuels must be treated to remove the salts from the fuels, and inhibitors must be added to prevent the vanadium in the fuel from corroding IC engine components. Treatment facilities exist, but their function is minimal. The primary reason for the shift away from the treatment of crude and residual fuels is one of economics. In today's market, it simply costs more to buy and treat the crude and residual oils than to purchase and burn the distillate oils.

The cost of flue gas desulfurization for IC engines does not appear to be reasonable from an economic viewpoint. Therefore, the only viable means of controlling SO_x emissions would be combustion of low-sulfur fuels. If users in urban or SO_x-sensitive areas decide to buy new engines and to use crude or residual oil as a fuel with these engines, then the local air pollution authorities could impose fuel restrictions on these engines. Such fuel restrictions would be entirely independent of the standards of performance from both a technological and enforcement viewpoint. That is, the absence of federal emission limits on SO_x would not prevent a local air pollution control district from setting such a standard since the engine would not have to be changed in order to meet the local standard. Thus, standards of performance are not recommended for SO_x emissions.

9.3 SELECTION OF AFFECTED FACILITIES

In sections 1.0 and 2.0 it was shown that NO_x emissions constitute the most significant pollutant emitted by stationary IC engines, and that large-bore (greater than 350 CID/cyl) engines account for over 75 percent of all NO_x emission from stationary engines. This section will establish criteria that define which large diesel, dual-fuel, and natural gas engines (referred to as "affected facilities") are to be affected by the proposed standards of performance. The objective here is to apply standards of performance to <u>significant sources</u> of NO_x emissions.

Thus, the following sections will present and explain the criteria that define affected facilities after considering the applications served by stationary engines, the number of units produced annually, and the incremental NO_x contributed by the annual production. The following discussions are subdivided by the three operational fuel types: diesel, dual-fuel, and natural gas. As will be discussed in the following paragraphs, this classification separates large-bore engines into three relatively distinct categories of engine applications. Initially, large-bore engines will be defined as those exceeding 350 CID/cyl. Then, if necessary, other criteria will be presented and explained to define affected diesel, dual-fuel, and natural gas engines.

The following discussion summarized an extensive study of the applications of large-bore engines. Many of the conclusions presented here are based on information concerning engine sales and applications during the past five years. This information was voluntarily submitted by engine manufacturers in response to Section 114 requests for information.[11] This information has not been cited for particular manufacturers since it is considered proprietary by the manufacturers.

Affected Diesel Engines

The primary high usage (large emissions impact), domestic application of large-bore (i.e., greater than 350 CID/cyl) diesel engines during the past five years has been for oil and gas exploration and production. These and other applications are illustrated in Figure 9-2.[12-17] As this figure shows, the market for prime (continuous) electric generation and other industrial applications all but disappeared after the 1973 oil embargo, but was quickly replaced by sales of standby electric units for building services, utilities, and nuclear power stations. The rapid growth in the oil and gas production market occurred because diesel units are being used on oil drilling rigs of various sizes. Sales of engines to export applications have also grown steadily since 1972, and are not a major segment of the entire sales market.

Medium-bore (from 35 to 350 CID/cyl) as well as large-bore engines are sold to oil and gas exploration, standby service, and other industrial applications. Furthermore, manufacturers of medium- and large-bore engines often compete for the same applications, although, in general, medium-bore engines have a cost advantage (lower $/hp). This is because the higher initial costs for a large-bore, heavy-duty, continuous-service engine more than offset their lower maintenance and fuel costs. This overlap in sizes is best illustratred in Figure 9-3 which shows a considerable number of medium- and large-bore engines in the 500- to 2000-horsepower range. Figure 9-4 shows the displacement per cylinder that

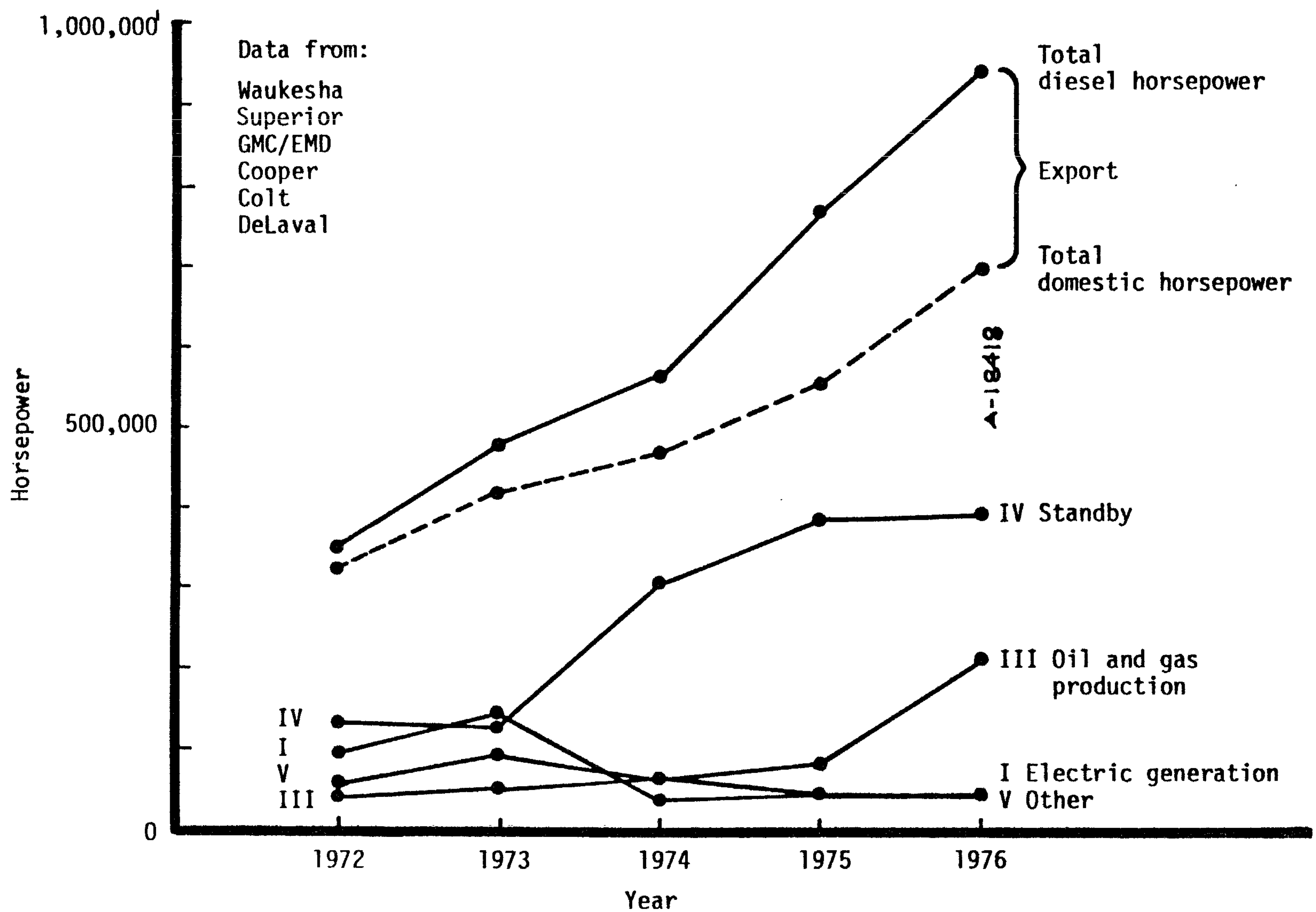


Figure 9-2. Sales of large-bore (>350 CID/cyl) diesel horsepower (from References 12-17).

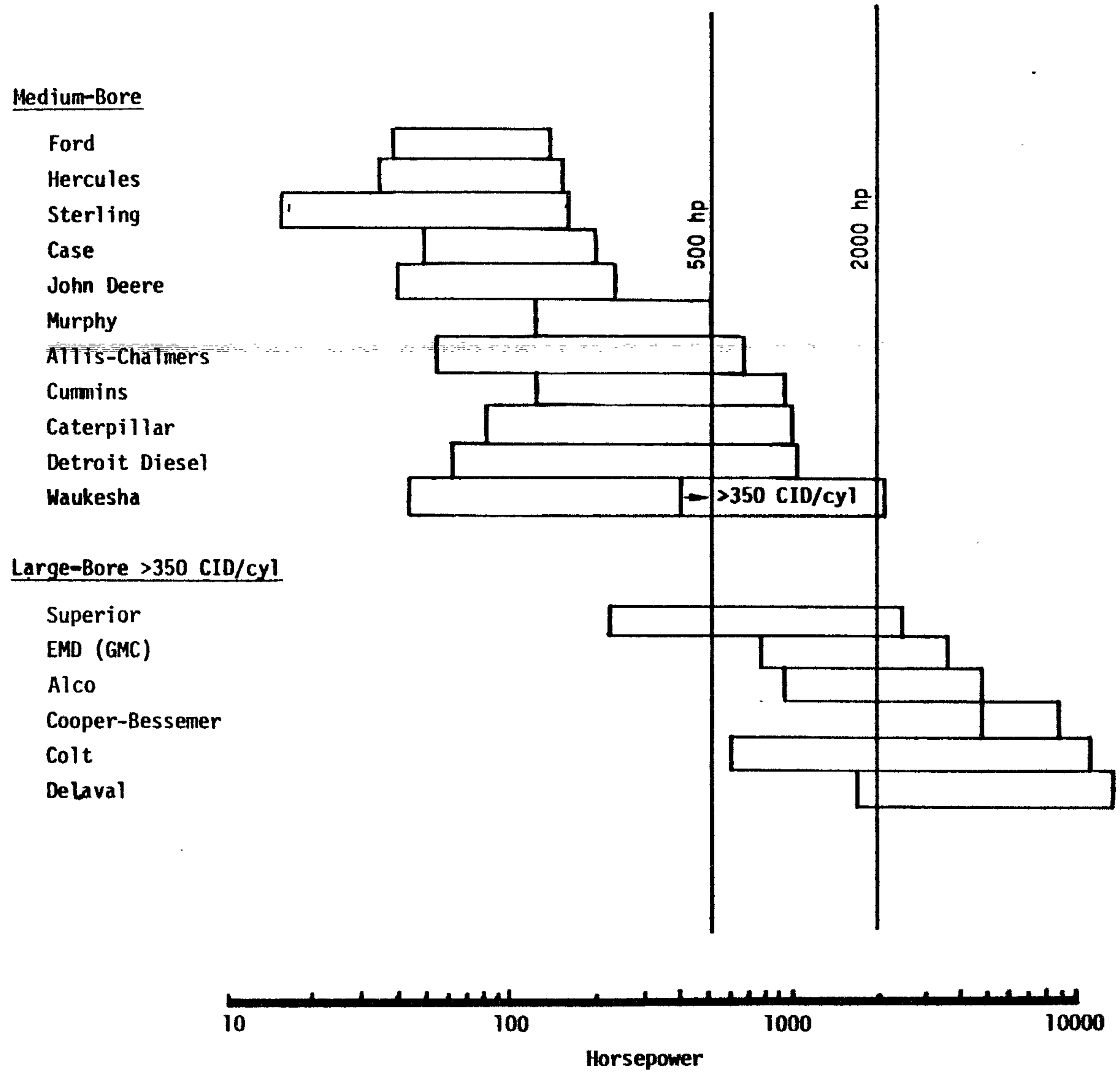


Figure 9-3. Manufacturers of diesel engines categorized by horsepower.

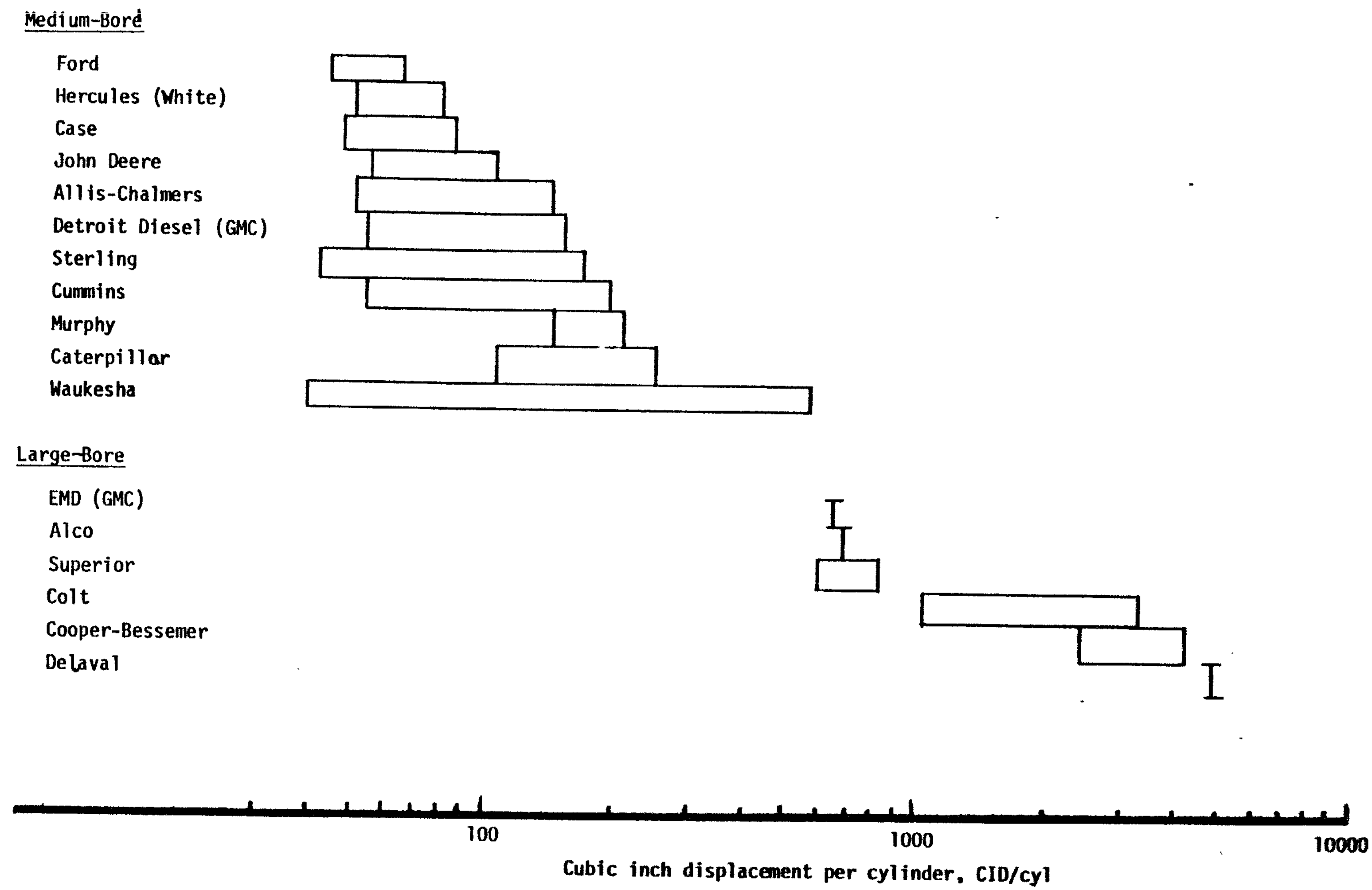


Figure 9-4. Manufacturers of diesel engines categorized by cubic-inch displacement per cylinder.

corresponds to the ranges of horsepower offered by the manufacturers shown in Figure 9-3. Table 9-4 shows the overlap for particular engine models.

The application with the greatest degree of overlap for medium and large-bore diesels is petroleum exploration. Smaller (250-to 1000-hp) medium-bore designs (e.g., Detroit Diesel, Cummins, and Caterpillar) are used on portable drilling rigs to drill or service 2500- to 5000-foot wells. These rigs are trailer-mounted or helicopter-transported; therefore, small, lightweight (approximately 4000-lb) engines are favored. In addition, multiple units are preferred to insure some backup power in the event one engine is down, ruling out a single unit of comparable total horsepower.

Larger horsepower engines are used in groups of three to five to provide 800 to 3000 hp for wells ranging in depth from 5000 to 25,000 feet. On most of these rigs, engines supply mechanical power to operate the drilling (rotary table), mud pumps, and hoisting equipment. In the larger units several engines from one manufacturer's engines operate pumps or generator sets for auxiliary power.[18] A relatively new approach is to generate AC power, rectify some of it for drilling power (variable load DC motors), and use the rest to drive AC auxiliaries. This approach is used primarily on offshore platforms, although there is interest in applying it to land-based sites despite its higher cost.

In conclusion, then, larger land-based drilling sites are the major areas of overlap of service provided by both large-bore and medium-bore manufacturers. These applications and baseload electric generation (to a lesser extent, since horsepower sales are small) have the most signifi-

TABLE 9-4. COMPARISON OF WAUKESHA, WHITE SUPERIOR, AND MEDIUM-BORE ENGINE MODELS GREATER THAN 500 HORSEPOWER

Manufacterer	Model	Number of Cylinders	Displacement per Cylinder, CID/CYL	Displacement, cubic inches	Type	Continuous Rated Horsepower	rpm
Waukesha	VHP	6	482	2,896	NA	411	1,200
Waukesha	VHP	6	482	2,896	TC	561	1,200
Waukesha	VHP	6	482	2,896	TC,AC	702	1,200
Waukesha	VHP	6	556	3,335	TC,AC	808	1,200
Waukesha	VHP	12	482	5,792	NA	818	1,200
Waukesha	VHP	12	482	5,792	TC	1,123	1,200
Waukesha	VHP	12	482	5,792	TC,AC	1,403	1,200
Waukesha	VHP	12	556	6,670	TC,AC	1,616	1,200
Waukesha	VHP	16	556	8,894	TC,AC	2,154	1,200
Cummins	VTA-1710-P KTA	12 12	143 192	1,710 2,300	TC,AC TC,AC	547 900	1,800 1,900
Caterpillar	D398TA D399TA	12 16	245 245	2,945 3,927	TC,AC TC,AC	750 1,000	1,200 1,200
Detroit Diesel	12V-149 16V-149	12 16	149 149	1,788 2,384	TC,AC TC,AC	810 1,080	1,800 1,800
Superior Division/Cooper	40-X-6 PTD5-6 40-X-8 PTDS-8	6 8	687/596 687/596	4,120/3,575 5,493/4,767	TC,AC TC,AC	790/675 820/945	1,000 900

cant NO_x emissions impact because they are high usage (approximately 6000 hr/yr). However, a greater-than-350-CID/cyl definition of affected facilities would result in some manufacturers (e.g., Waukesha) being subject to control technology development costs, while medium-bore engines (of same power, but more cylinders) serving identical applications would not incur these costs. This is clearly undesirable since this definition would unfairly place some large-bore engines in a less competitive position than similarly sized (by horsepower), smaller-bore designs.

On the other hand, applying the standards of performance to medium-bore engines serving the same applications as large-bore designs would increase the number of affected facilities from about 200 to about 2000 units per year (based on 1976 sales information) but consequently further reduce NO_x emissions. Medium-bore sales accounted for significant NO_x emissions in 1976 (approximately 12,500 megagrams). It is estimated that approximately 25 percent, or about 500 of these units, in high usage applications accounted for most of the medium-bore NO_x emissions, since most of the remainder of these units were sold as standby generator sets. Though the potential achievable NO_x reduction is significant, considering this large number, and the remoteness and mobility of petroleum applications, this alternative would create serious enforcement difficulties. Additionally, this alternative causes the standard to apply to lower power engine models with fewer number of cylinders competing in different stationary markets with other unregulated engines. Consequently, a definition is required that distinguishes between large-bore engines that compete with medium-bore high power engines used for baseload electrical generation from large-bore engines that compete solely with other large-bore engines.

One approach would be to define diesel engines covered by standards of performance as those exceeding 560 CID/cyl. This alternative would exclude engines presently manufactured by Waukesha as well as those produced by Caterpillar, Detroit Diesel, and Cummins. This definition, however, shifts the area of overlap in horsepower between regulated and unregulated engines to other large-bore diesel manufacturers. This situation is depicted in Figure 9-5, which illustrates the relationship between displacement per cylinder and rated (continuous) horsepower. All Waukesha engines are excluded above the 560 CID/cyl limit. However, Superior's diesel engines ranging in size from 596- to 825-CID/cyl would be subject to standards. These engines compete in very few cases with Waukesha diesel engines. Raising the limit to 700-CID/cyl would exclude Superior engines in the 500- to 100-hp range, but it would also exclude EMD and Alco models, which compete with Colt (700-CID/cyl, hence regulated) in the 1000- to 3000-hp range. Establishing a 560-CID/cyl definition, therefore, appears to be a viable method of excluding engines which compete with medium-bore designs without introducing a significant overlap problem at a different power level.

After considering the sizes and displacements offered by each diesel manufacturer and the applications served by diesel engines, a 560-CID/cyl definition was selected as a reasonable approach for separating large-bore engines that compete with medium-bore engines from large-bore engines that compete solely with each other. This cylinder displacement size was chosen because engines below this size are generally used for

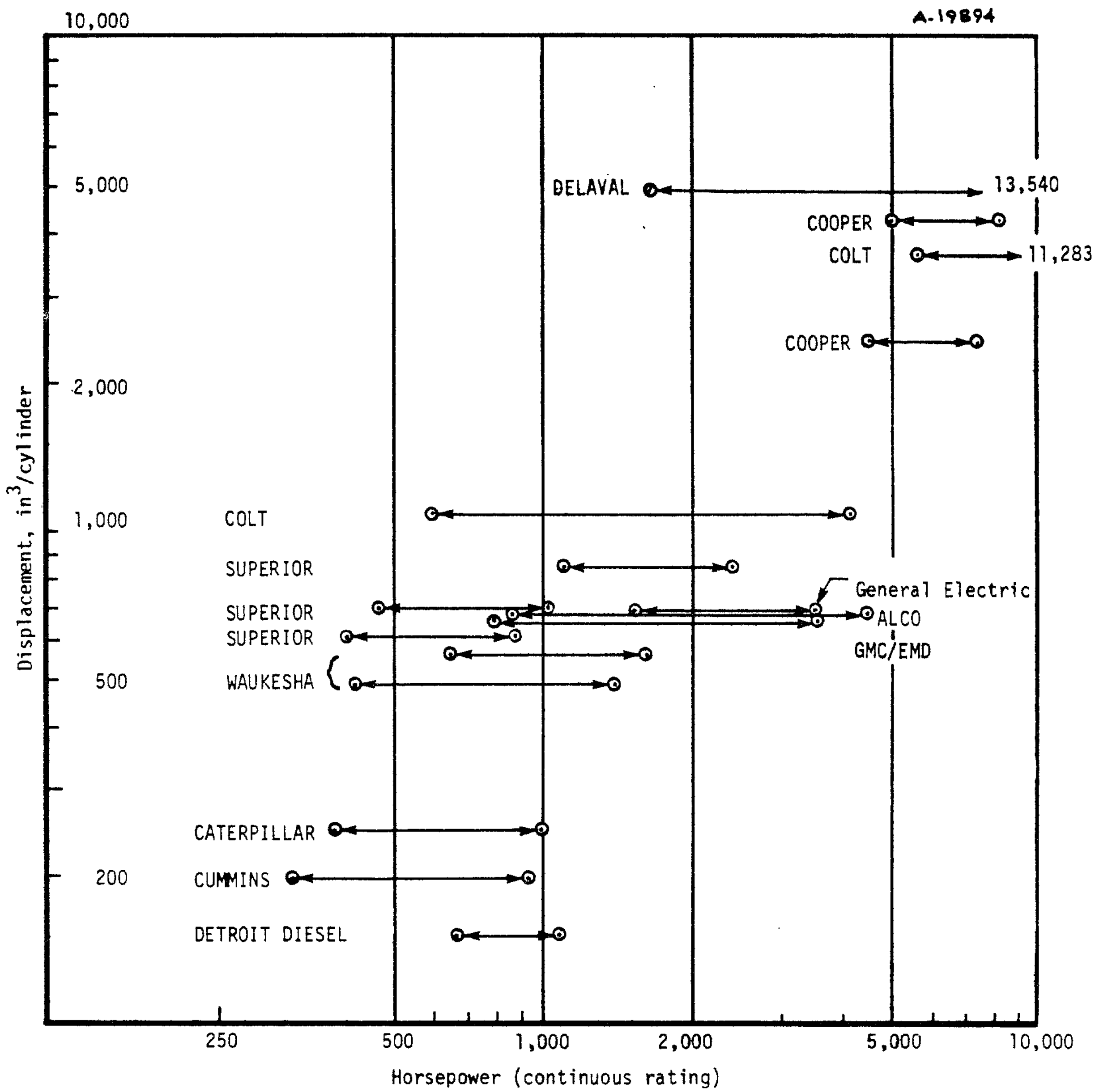


Figure 9-5. Displacement per cylinder versus continuous rated horsepower for diesel engines.

different applications than those above it. Therefore, it is recommended that diesel engines greater than 560 CID/cyl be affected by standards of performance.

Affected Dual-Fuel Engines

The concept of dual-fuel operation was developed to take advantage of both compression ignition performance and inexpensive natural gas. These engines have been used almost exclusively for prime electric power generation. Figure 9-6[19-22] illustrates, however, that shortages of natural gas and the 1973 oil embargo have combined to significantly reduce the sales of these engines in recent years. The few large-bore units that were sold (11 in 1976) were all greater than 350 CID/cyl. In fact, with the exception of Superior Division/Cooper and Stewart-Stevenson (modified Detroit Diesel engine) products, all were greater than 500 horsepower and 1000 CID/cyl as shown in Figures 9-7 and 9-8. Moreover, nearly all of the dual-fuel engines sold since 1972 have been larger than 1000 hp. Only Stewart-Stevenson manufactures dual-fuel engines less than 560 CID/cyl. Sales of these units are less than 100 units per year and about 70 percent of these are exported.[23]

Although a greater-than-350-CID/cyl limit would subject nearly all new dual-fuel sources to standards of performance (only engines manufactured by Stewart-Stevenson would be excluded), it is recommended that the definition chosen to define affected diesel engines (560 CID/cyl) also be applied to dual-fuel engines. The reason is that supplies of natural gas are likely to become even more scarce, possibly causing recently installed or future dual-fuel units to convert to diesel fuel operation. Any additional diesel engines that would be created by con-

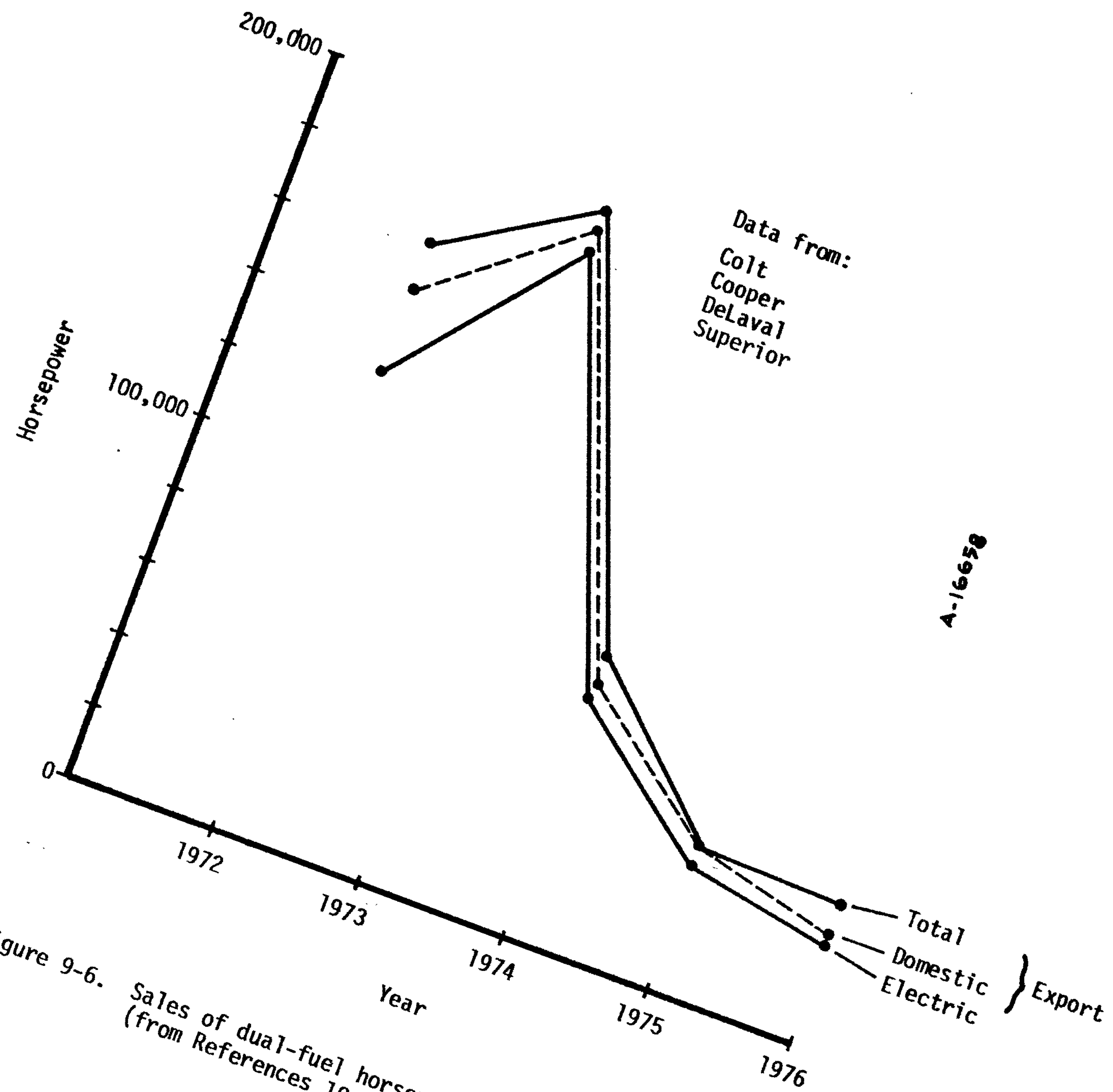


Figure 9-6. Sales of dual-fuel horsepower during the past 5 years (from References 19 to 22).

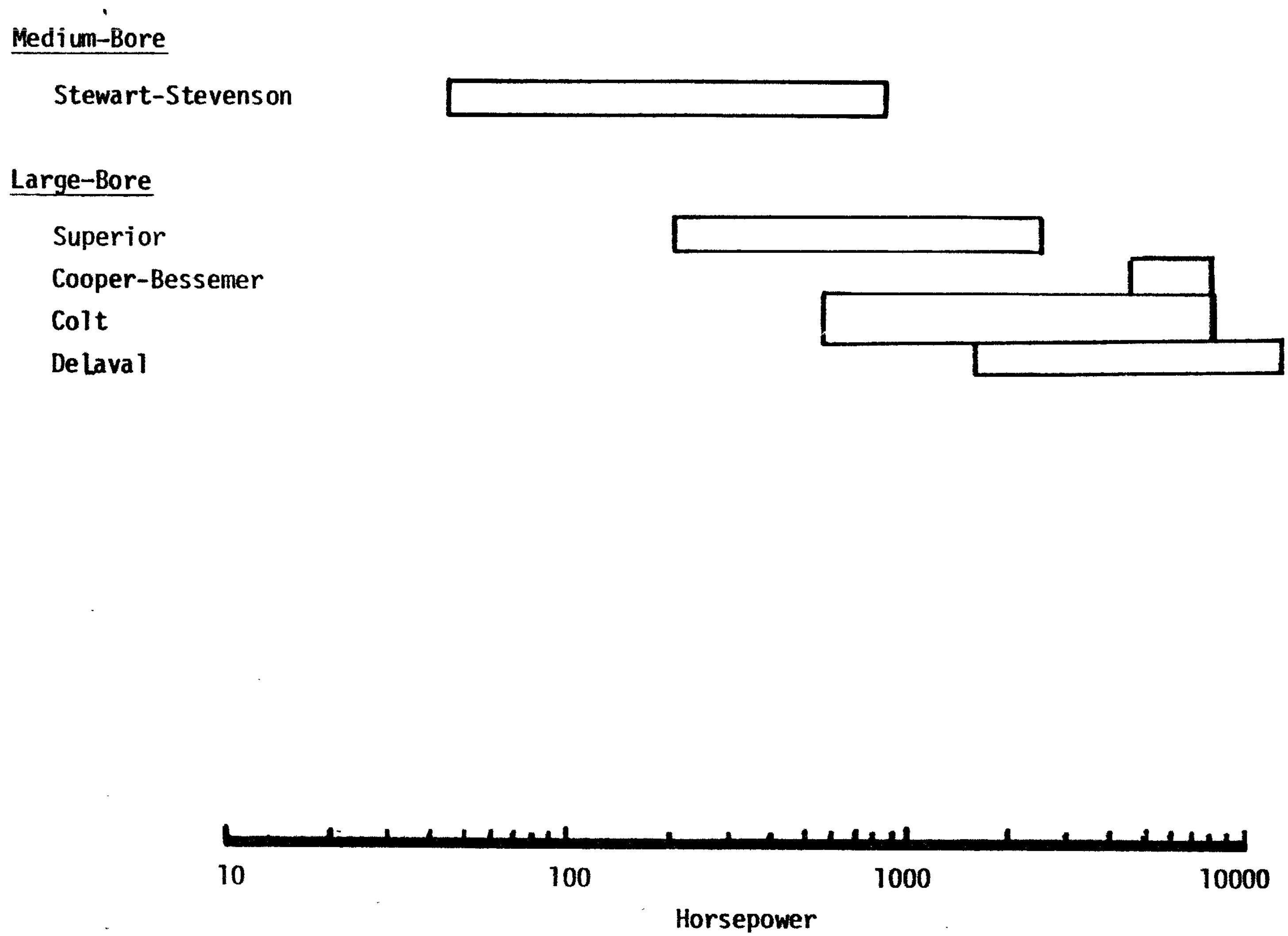


Figure 9-7. Manufacturers of dual-fuel engines categorized by horsepower.

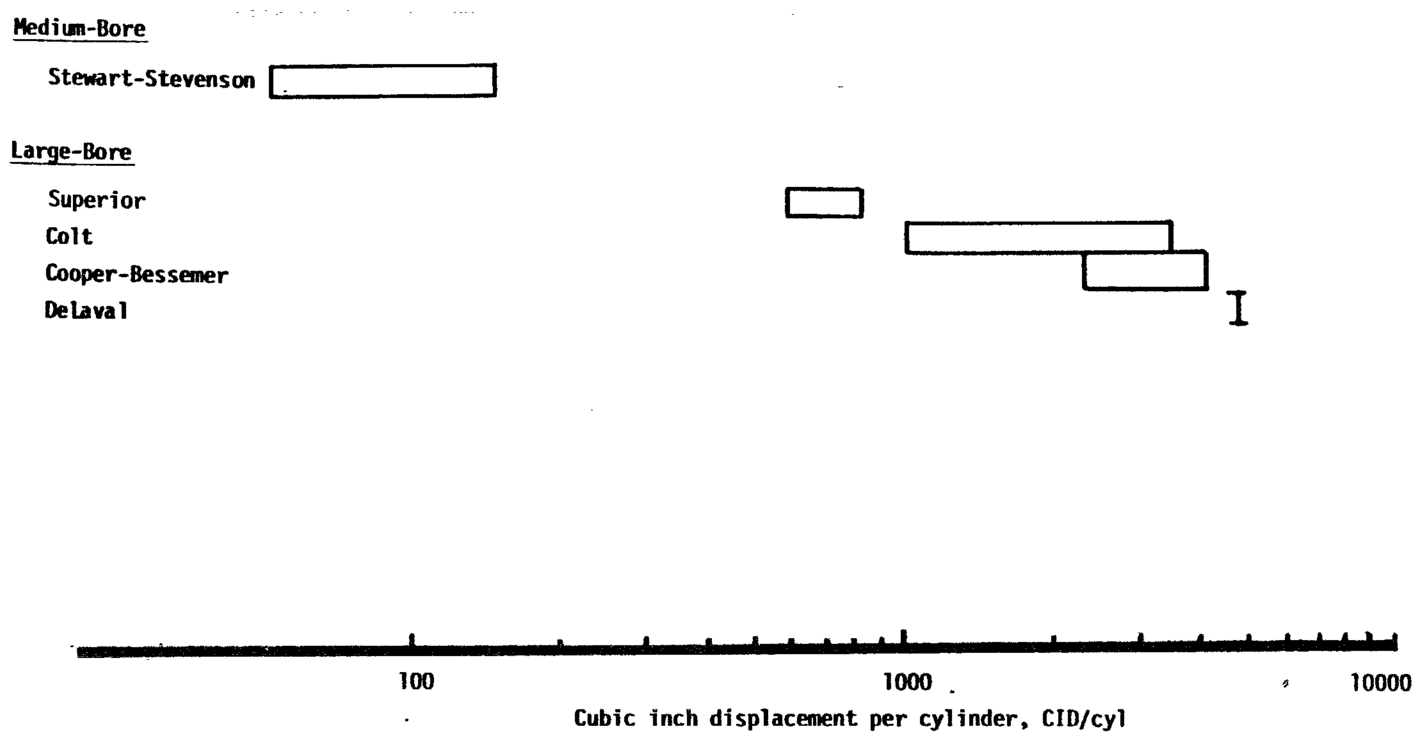


Figure 9-8. Manufacturers of dual-fuel engines categorized by cubic-inch displacement per cylinder.

version from dual-fuel operation should be subject to the same regulations applicable to other large diesel engines.

Affected Gas Engines

The primary application of large (greater than 350 CID/cyl) gas engines during the past five years has been for oil and gas production. The primary uses are to power gas compressors for recovery, gathering, and distribution. Figure 9-9[24-29], based on manufacturer's data from response to the June 16, 1976 Section 114 requests for information, illustrates that 75 to 80 percent of all gas engine horsepower sold during the past five years was used for these applications.

During this time sales to pipeline transmission applications declined. Pipeline applications combined with standby power, electric generation, and other services (industrial and sewage pumping). These other applications accounted for the remaining 20 to 25 percent of horsepower sales. The growth of oil and gas production applications during this period corresponds to the increasing efforts to find new, or recover marginal, gas reserves and distribute them to the existing pipeline transmission network.

Figure 9-10 illustrates the number of gas engines sold for five size groups during the past five years. The large number of smaller-than-500-hp engines that were sold during this period are one or two cylinder engines used on oil well beam pumps and for natural gas well recovery and gathering. Most of the other larger gas engines that were sold during this period ranged from 500 to 2000 hp. In 1976, approximately 400 engines in this size range were sold, primarily for oil and gas production (see Figure 9-9). Most of these gas engines were manufactured by Cater-

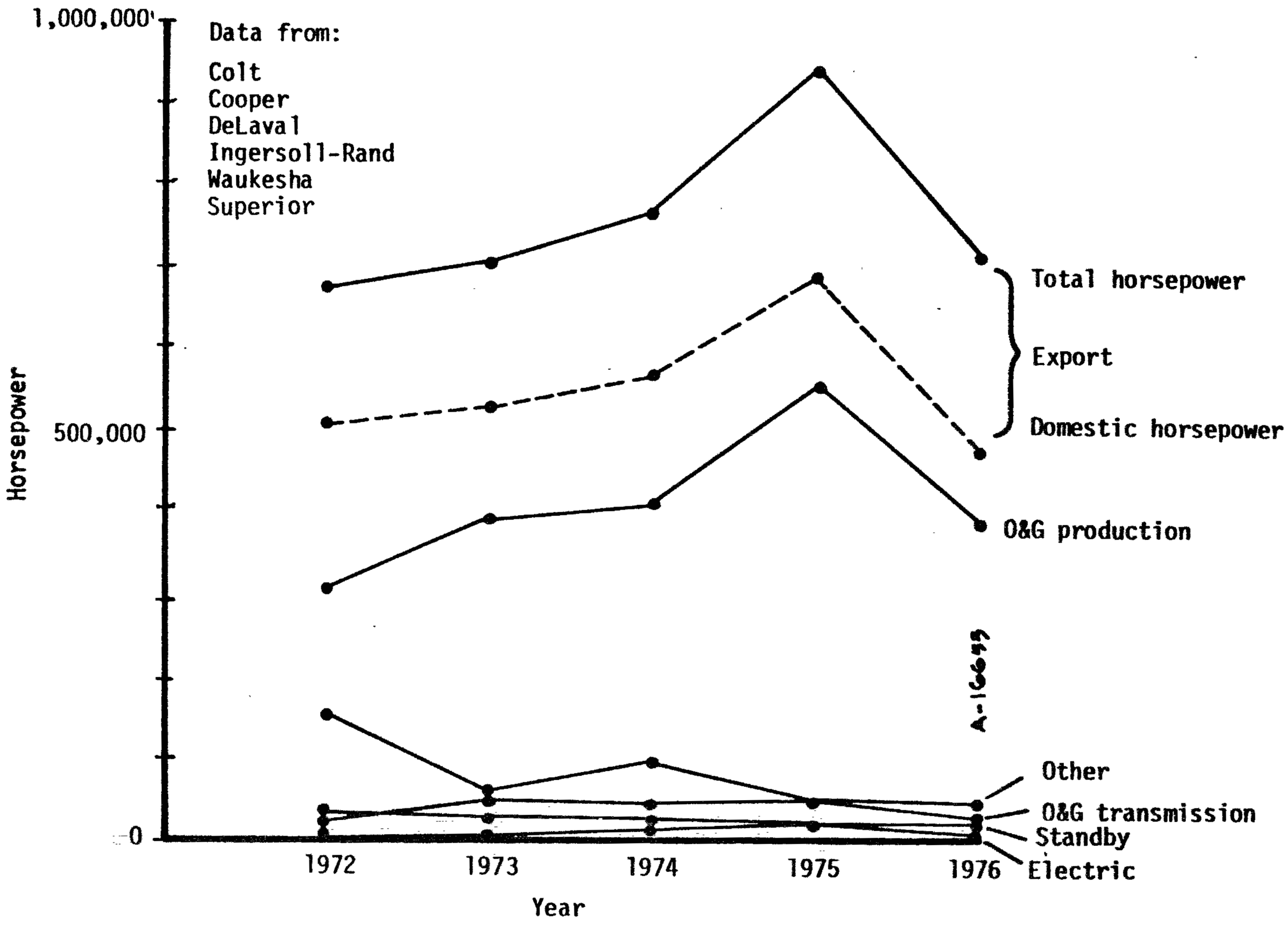


Figure 9-9. Sales of gas engine horsepower by application for the past 5 years (absolute levels shown for domestic applications from References 24 to 29).

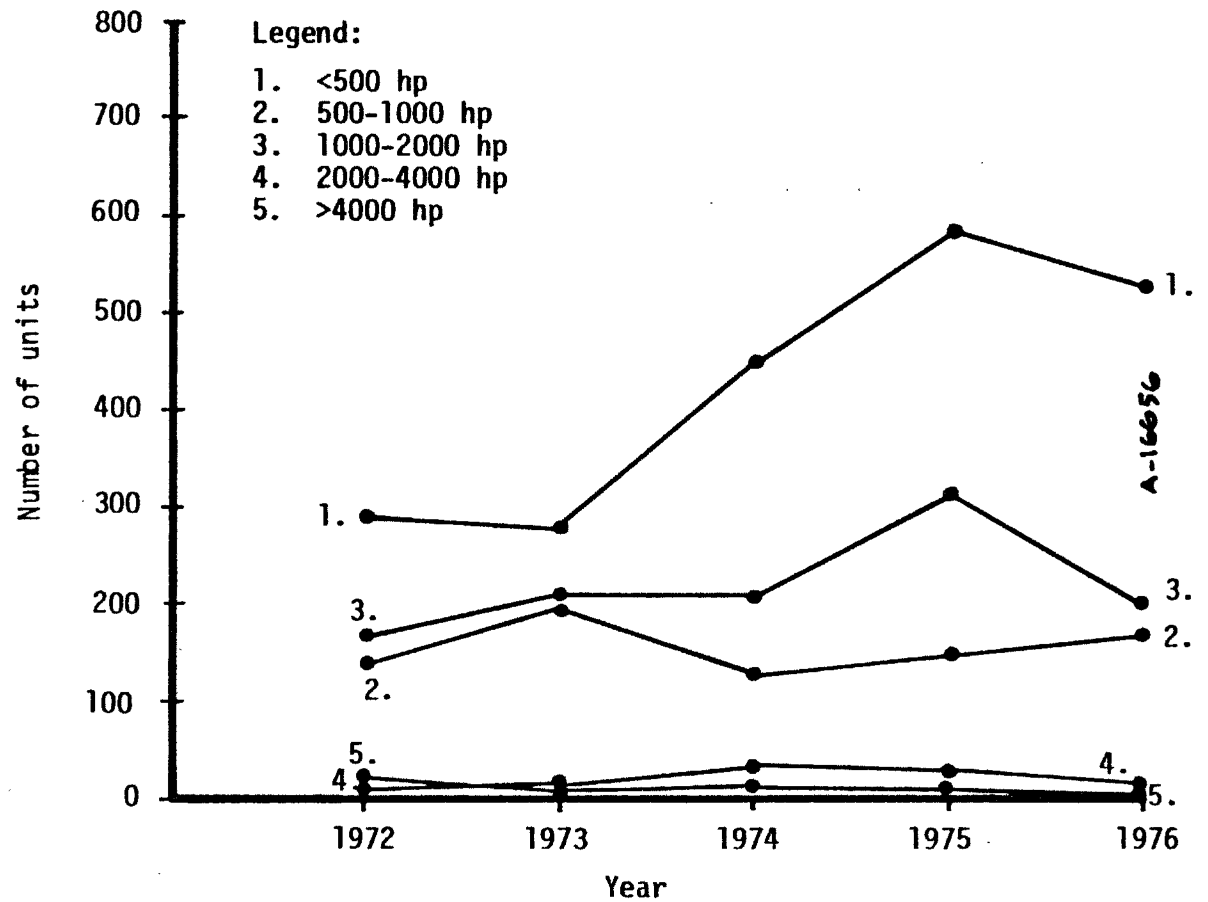


Figure 9-10. Size distribution of gas engines sold during the past 5 years.

pillar, Cooper, Waukesha, and White Superior.

With the exception of standby service, all the applications of Figure 9-9 are high usage (approximately 6000 hr/yr), and therefore, contribute significant NO_x emissions. It is estimated that the 400,000 horsepower of large-bore gas-engine capacity sold for oil and gas production applications in 1976 emitted 34,900 megagrams of NO_x emissions, or nearly three times more NO_x than was emitted by the 200,000 horsepower of large-bore diesel engine capacity (greater than 350 CID/cyl) sold for the same application in that year (see Section 3.1). Thus, large-bore gas engines are primary contributors of NO_x emissions from new stationary IC engines, and standards of performance should be directed particularly at these sources.

If affected engines were defined as those greater than 350 CID/cyl, then all manufacturers of gas engines greater than 500 hp, except Caterpillar, would be affected by proposed standards of performance. However, large Caterpillar gas engines range from 225 to 930 horsepower, and therefore, compete with the other large-bore manufacturers (particularly Waukesha). Figures 9-11 and 9-12 show more clearly the overlap in horsepower provided by manufacturers of engines of various cylinder displacements. Therefore, a greater-than-350-CID/cyl limit would give one manufacturer an unfair competitive advantage over other large-bore engine manufacturers. Thus, although a greater-than-350-CID/cyl limit would subject most significant gas engine sources of NO_x emissions to potential standards of performance, this definition should be revised based on the following considerations:

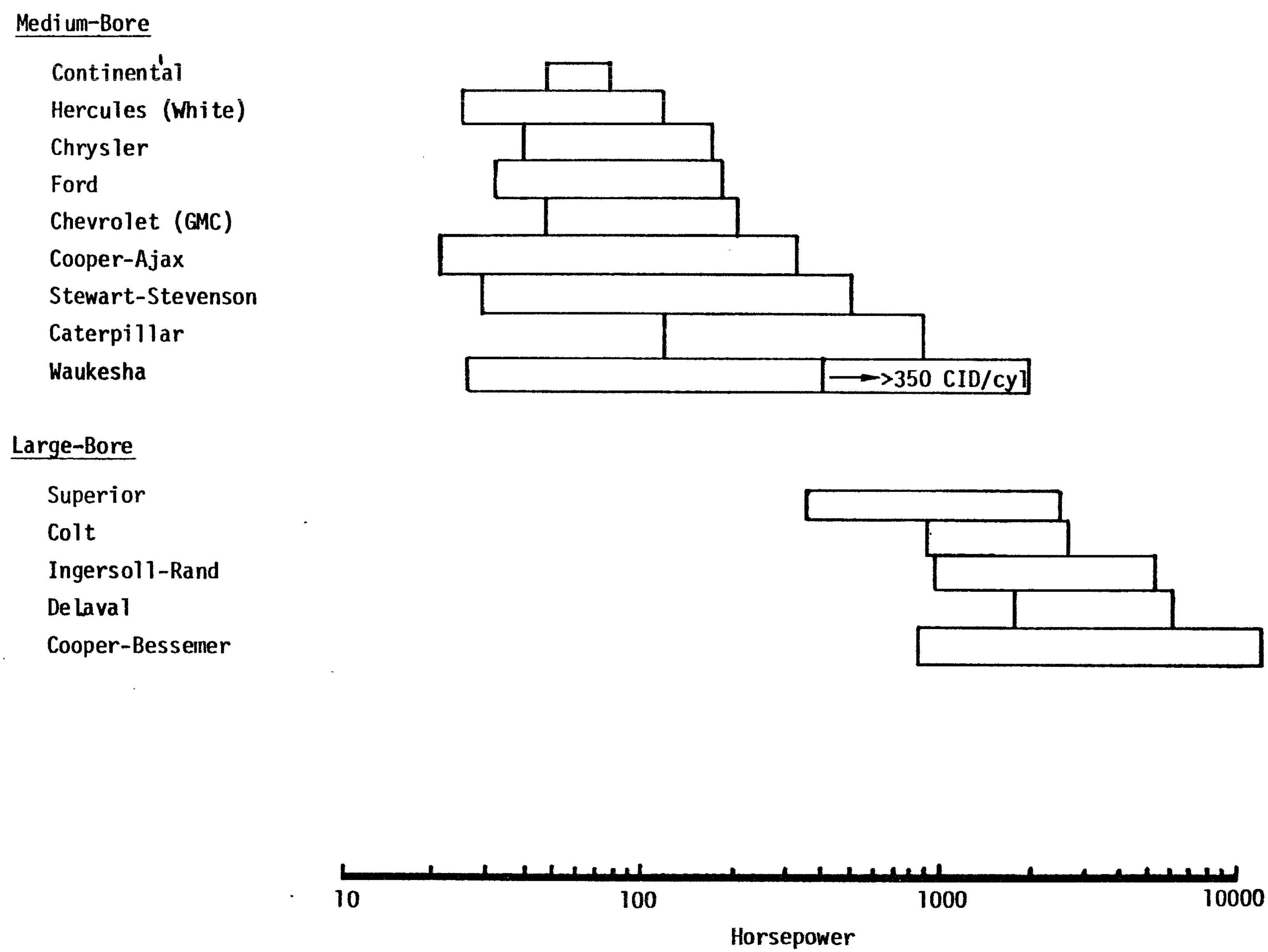


Figure 9-11. Manufacturers of gasoline and natural gas engines categorized by horsepower.

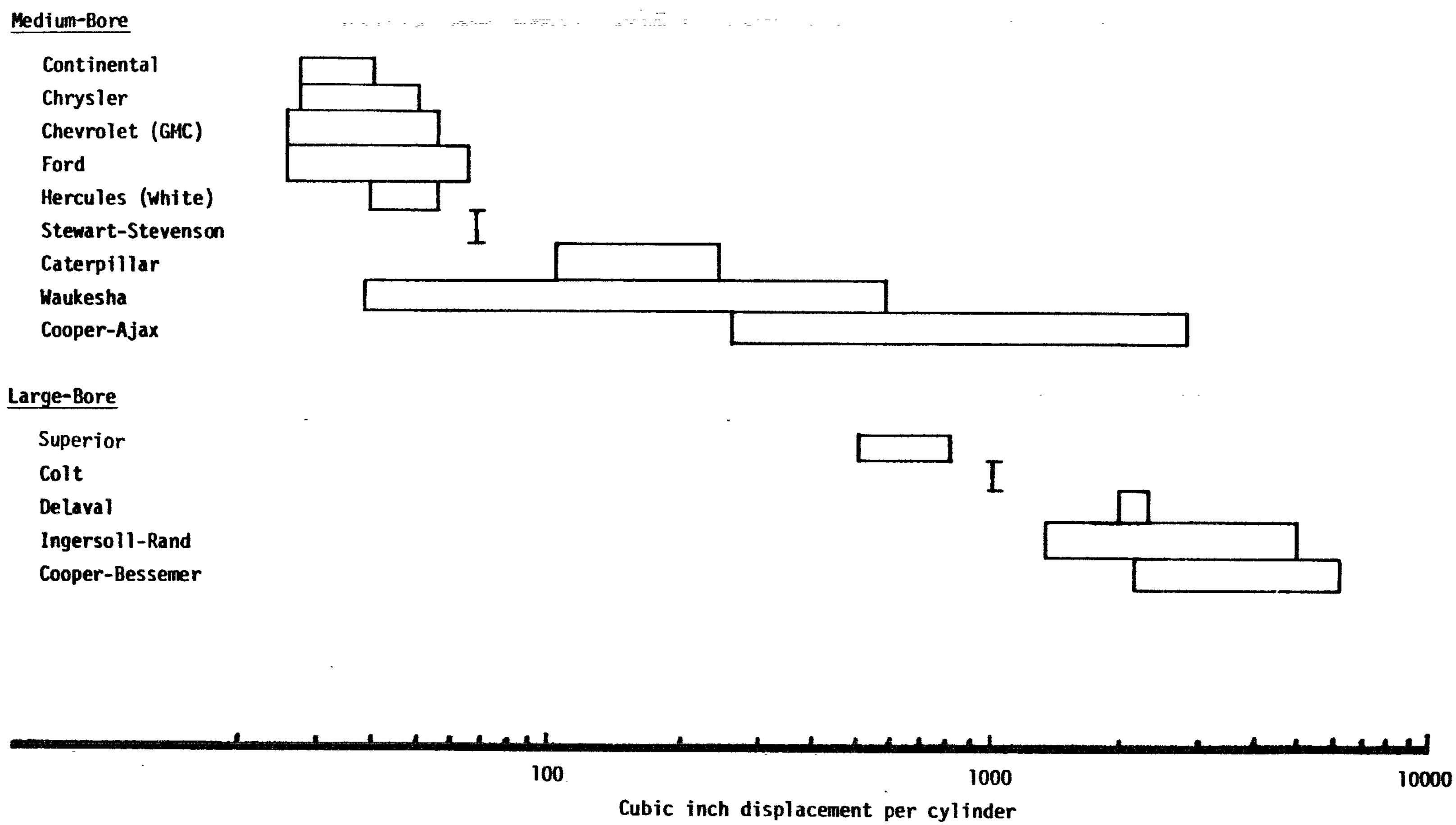


Figure 9-12. Manufacturers of gasoline and natural gas engines categorized by cubic-inch displacement per cylinder.

- The greater-than-350-CID/cyl definition excludes the only other manufacturer (Caterpillar) of gas engines greater than 500 hp. Caterpillar gas engines compete directly with the large gas engines manufactured by Cooper, Waukesha, and White Superior, which would be regulated.
- No emissions have been measured or control techniques demonstrated for 1- and 2-cylinder engines which would be included in potential standards of performance by the existing greater than 350 CID/cyl limit.

The first observation suggests that the definition should be lowered, or another definition adopted, to include the large Caterpillar engines that compete in identical applications with Cooper, Waukesha, and White Superior units. Although Caterpillar has not reported controlled emissions data for their gas engines, control techniques have been demonstrated on other similar gas engines and should be effective when applied to Caterpillar engines, since they are all similar in design (i.e., carbureted and gas injected engines that are either turbocharged and aftercooled or naturally aspirated).

Table 9-5 compares large Caterpillar gas engines with Waukesha models that are greater than 350 CID/cyl. As this comparison illustrates, Caterpillar engines with smaller displacements per cylinder and greater numbers of cylinders serve about the same power range as do the larger Waukesha engines. On the basis of this table, either of the following two steps would subject Caterpillar gas engines to potential standards of performance:

TABLE 9-5. COMPARISON OF LARGE CATERPILLAR GAS ENGINES WITH WAUKESHA GAS ENGINES >350 CID/CYL

MFG/Model	#CYL	CID/CYL	Continuous HP @ 1,200 rpm
Caterpillar			
G399	16	245	600 to 930
G398	12	245	450 to 700
G379	8	245	300 to 450
G353	6	245	225 to 350
G342	6	207	200 to 295
Waukesha			
L7042	12	587	888 to 1,359
L5790	12	482	726 to 1,114
L5108	12	426	645 to 987
F3521	6	587	432 to 674
F2895	6	482	360 to 558

- Select a definition of greater than 240 CID/cyl
- Define affected gas engines as those greater than 350 CID/cyl or greater than or equal to 8 cylinders and greater than 240 CID/cyl

Both measures would essentially include only Caterpillar engines in the same power range as Waukesha. The second definition has a slight advantage over the first since it includes only Caterpillar engines that have Waukesha counterparts of about the same power (note that the greater-than-240-CID/cyl definition alone would include the Caterpillar G353, which has no large Waukesha counterpart). Therefore, the greater-than-350-CID/cyl or greater-than-or-equal-to-8 cylinders and greater-than-240-CID/cyl definition of affected gas engines is recommended.

With regard to one and two cylinder engines, it is recommended that they be excluded from potential standards of performance. This suggestion can be supported considering:

- At present these engines account for less than 10 percent of all gas engine horsepower and, therefore, are less significant NO_x emitters than the larger gas engines used for oil and gas production
- These sources are numerous and widely dispersed in remote locations
- These engines are low rated* and therefore, probably have lower NO_x emissions than the larger higher-rated gas engines

In addition to these factors, consideration should be given to the

*Operate at a small fraction of their potential power output.

undeveloped control technology for these engines. A spokesman for one manufacturer noted that they are only currently preparing to measure NO_x emissions from their one- and two-cylinder engines. Therefore, it is recommended that all one- and two-cylinder gas engines be exempted from potential standards of performance.

In summary, then, it is recommended that the following criteria define gas engines that are to be affected by standards of performance:

- Affected facilities are defined as engines that are either <u>greater than 350-CID/cyl</u> or <u>greater than 8-cylinder</u> and <u>greater than 240-CID/cyl</u>
- All one or two cylinder gas engines are exempt from standards of performance

9.4 SELECTION OF BEST SYSTEM OF EMISSION REDUCTION

As discussed in Chapter 4, four emission control techniques, or combinations of these techniques, have been identified as demonstrated NO_x emission reduction systems for stationary large-bore internal combustion engines. These techniques are: (1) retarded ignition or fuel injection, (2) air-to-fuel ratio changes, (3) manifold air cooling, and (4) derating power output (at constant speed). In general, all four techniques are applied by changing an engine operating adjustment. Manifold air cooling, however, may require a larger heat exchanger, and air-to-fuel changes may require turbocharger resizing.

These control techniques, described in Chapter 6, reduce NO_x emissions primarily by lowering peak flame temperatures. Some of the techniques may result in increased fuel consumption and/or engine maintenance.

Fuel injection retard is the most effective NO_x control technique for diesel-fueled engines, achieving maximum NO_x reductions of about 65 percent. Similarly, air-to-fuel ratio change is the most effective NO_x control technique for natural gas engines, achieving maximum NO_x reductions of about 80 percent. Both retard and air-to-fuel ratio changes are effective in reducing NO_x emissions from dual-fuel engines, achieving maximum NO_x reductions of about 70 percent.

Other NO_x emission control techniques exist but are not considered feasible alternatives. These techniques, also described in Chapter 6, include exhaust gas recirculation (EGR), combustion chamber modification (CCM), water induction, and catalytic reduction.

Exhaust gas recirculation tests have shown effective NO_x reductions; however, the necessity for cooling the recirculated gas may lead to contamination of flow passages in the cooling heat exhanger as well as in the engine turbocharger and aftercooler. At present there is insufficient data on which to base conclusions and more development is required. Therefore, it is not considered a demonstrated emission control technique.

Data from smaller-bore diesel engines indicate that combustion chamber configuration has a significant effect on NO_x emissions. However, none of the domestic large-bore engine manufacturers has thoroughly studied the effects of modified combustion chamber geometries on NO_x emissions. Manufacturers have estimated that an extensive development program of three to five years would be required to establish the emission benefits of such a major engine redesign. The majority of the existing engines are primarily long-established designs that have been refined over the years to improve fuel economy and maintenance. Since there is insufficient data to draw conclusions, combustion chamber modification is not considered a demonstrated emission control technique.

The effect of water induction in large stationary internal combustion engines is similar to the effect in gas turbines. Significant NO_x reductions are achieved due to the quenching effect of the presence of water. However, as discussed in Section 4.4.7, tests with water induction in large stationary internal combustion engines have shown unacceptable deposit build-up on the exhaust/intake valves from the use of untreated water, and severe lubricating oil contamination. Therefore, water induction is also not considered a demonstrated control technique.

Catalytic reduction of NO_x in large stationary internal combustion engines is difficult to achieve and the capital cost could be high. Most large stationary internal combustion engines operate at air-to-fuel (i.e., mass flowrate [g/hr] of air into an engine divided by the mass flowrate of fuel [g/hr]) ratios that are typically much greater than stoichiometric and consequently the engine exhaust is characterized by high oxygen concentrations. Existing automotive catalytic converters, however, operate near stoichiometric conditions (i.e., low exhaust oxygen concentrations). These automobile catalysts are not effective in reducing NO_x in the presence of high oxygen concentrations. Consequently, entirely different catalyst systems would be needed to reduce NO_x emissions from large stationary internal combustion engines. Although such catalyst systems are currently under development and have been demonstrated for one very limited application (i.e., fuel-rich naturally aspirated gas engines), they have not been demonstrated for the broad range of IC engines manufactured, such as turbocharged engines, fuel-lean gas engines, or diesel engines. For these engines the reduction of NO_x by ammonia injection over a precious metal (e.g., platinum) catalyst appears promising with NO_x reductions of approximately 90 percent having been reported; however, the cost of such a system is high.

For a typical 1000 horsepower engine approximately 2 cubic feet of honeycomb catalyst (platinum based) would be required to ensure proper operation of the system. The cost of the catalyst was estimated at \$1500/cubic foot (in 1973). Assuming that the engine costs \$150/hp and that the cost of the catalyst accounts for about one-half the cost of the whole system (container, substrate, and catalyst), the capital investment for this control system represents approximately four percent of the engine purchase price.

The amount of ammonia required for an ammonia/catalyst NO_x reduction system will depend on the NO_x emission rate (g/hp-hr). Based on uncontrolled NO_x emission rates of 9 to 22 g/hp-hr, and the cost of \$150/ton for the ammonia, the cost impact of injecting ammonia is approximately 5 to 15 percent of the total annual operating costs (\$/hp-hr) for natural gas engines. When this operating cost is combined with the capital cost of the catalytic system discussed above, the total cost increase is about 25 percent. Therefore, in continuous service applications this system is expensive compared to control techniques such as retard or air-to-fuel ratio changes.

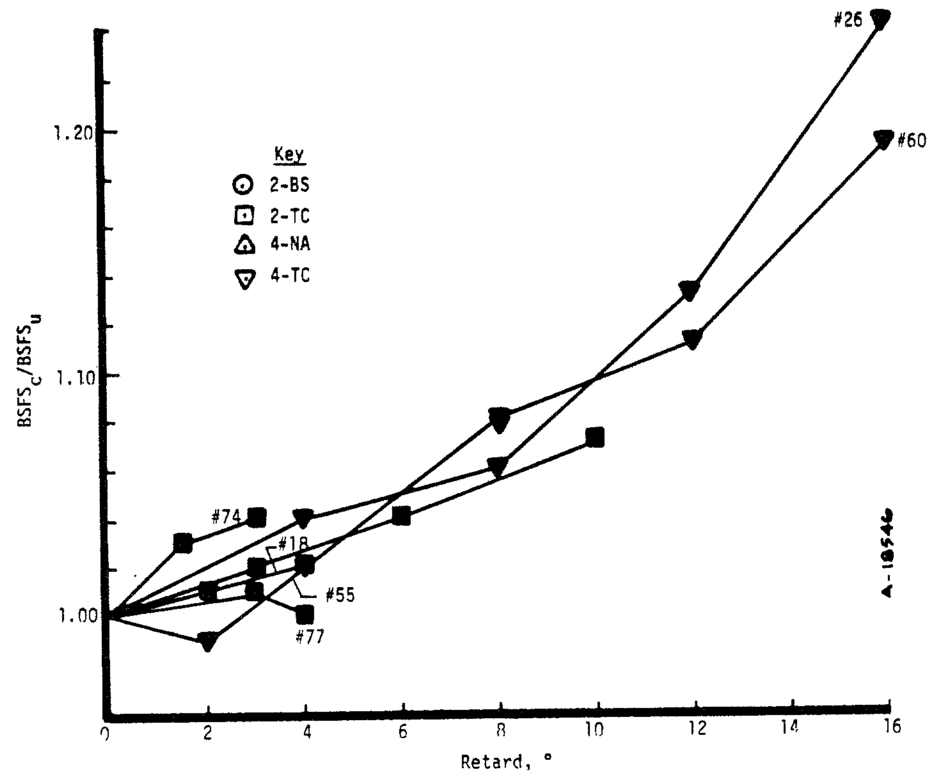
It is also important to note that the consumption of ammonia can be expressed as a quantity of fuel since natural gas is generally used to produce ammonia. Assuming a conservative NO_x emission rate of 20 g/hp-hr, and engine heat rate of 7500 Btu/hp-hr, a heating value of 21,800 Btu/lb for natural gas, and a requirement for approximately 900 lbs of gas per ton of ammonia produced, then the ammonia necessary for the catalytic reduction has the same effect on the supply of natural gas as a 2-percent increase in fuel consumption. Additional fuel is required to operate the plant which produces the ammonia.

Catalytic reduction, therefore, is currently not a demonstrated NO_x emission control technique which could be used by all IC engines. Consequently, although catalytic reduction of NO_x emissions could be used in a few isolated cases to comply with standards of performance, it could not be used as the basis for developing standards of performance which are applicable to all IC engines.

In summary, four emission control techniques have been identified as demonstrated NO_x emission reduction systems for stationary large-bore internal combustion engines. These techniques are: (1) retarded ignition or fuel injection, (2) air-to-fuel ratio changes, (3) manifold air cooling, and (4) derating power output (at constant speed). Fuel injection retard is the most effective NO_x control technique for diesel-fuel engines and air-to-fuel ratio change is the most effective NO_x control technique for gas engines. Either technique is effective for dual-fuel engines.

The data and information presented in Chapters 4 and 6 clearly indicate that application of the control techniques mentioned above will reduce NO_x emissions from internal combustion engines. It is not immediately clear, however, from this data and information whether the application of these emission control techniques to all IC engines would reduce NO_x emissions to a specific level due to inherent differences in the uncontrolled emission characteristics of various engines. In general, engines with high uncontrolled NO_x emission levels have relatively high controlled NO_x emission levels and engines with low uncontrolled NO_x emission levels have relatively low controlled NO_x emission levels. To eliminate these inherent differences in NO_x emission characteristics among various engines, the data were analyzed in terms of the degree of reduction in NO_x emissions as a function of the degree of application of each emission control technique. Figures 4-27 and 4-31, reproduced here as Figures 9-13 and 9-14, illustrate the overall effectiveness of ignition retard and air-to-fuel ratio changes for reducing NO_x emissions. For example, in Figure 9-13, the application of approximately eight of ignition retard results in about 40 percent reduction of NO_x emissions. Thus, the data presented in Chapters 4 and 6 demonstrate that the same degree of application of each of these four NO_x emission control techniques -- i.e., (1) retarded ignition or fuel injection, (2) air-to-fuel ratio changes, (3) manifold air cooling, and (4) derating power output (at constant speed) -- will result in essentially the same degree of reduction of NO_x emissions from all large stationary internal combustion engines. Consequently, the ability to achieve certain percentage reductions in NO_x emission levels is clearly demonstrated.

As can be seen from Figures 9-13 and 9-14, those included in



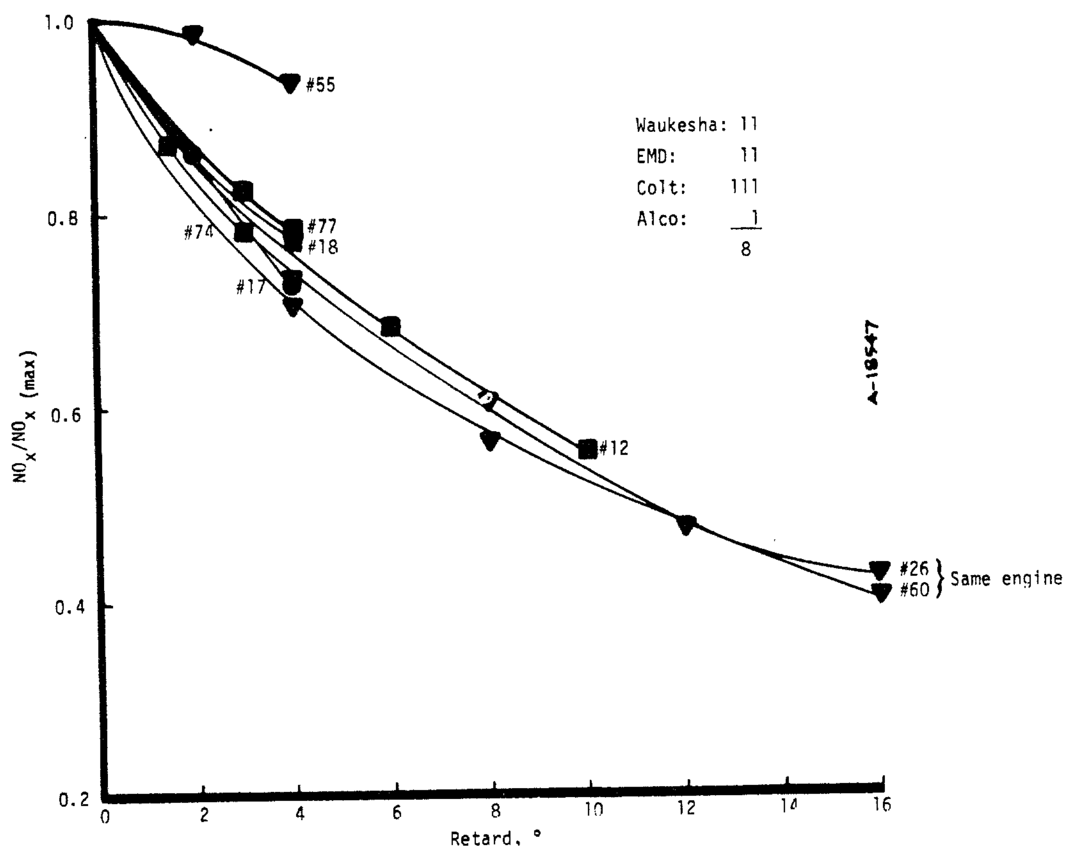


Figure 9-13. Effect of different amounts of retard on NO_X emissions and fuel consumption for diesel engines.

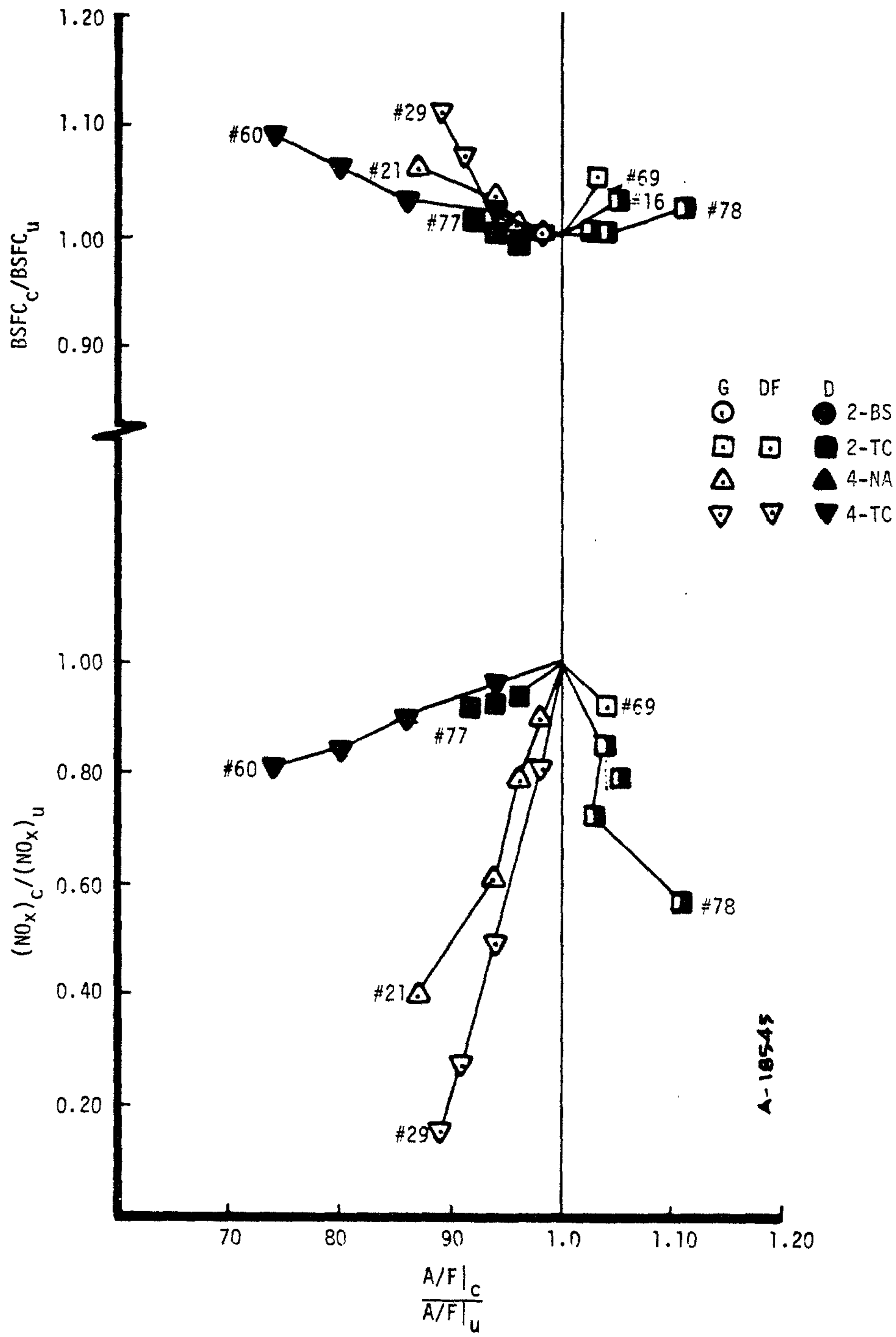


Figure 9-14. Effect of A/F changes on NO_x emissions and fuel consumption.

Chapters 4 and 6, a wide range of regulatory options (i.e., basis for standards) is available. The greatest reductions in NO_x emissions, achieved with some degree of consistency by the use of these four demonstrated NO_x control techniques, was approximately 60 percent. Therefore, 60 percent reduction was initially selected in Chapter 6 as the most stringent regulatory option that could serve as the basis for the standards. Alternative regulatory options of 20 and 40 percent reduction were selected as representative of less stringent basis for standards.

Subsequent review and analysis, however, indicate that technical/hardware considerations limit the percentage NO_x reduction that can be achieved in practice. Generally ignition retard in excess of eight degrees in diesel-fueled engines frequently leads to unacceptably high exhaust temperatures, resulting in exhaust valve and/or turbocharger turbine damage. Similarly, changes in the air-to-fuel ratio in excess of five percent in gas engines frequently leads to excessive misfiring or detonation which could lead to a serious explosion in the exhaust manifold. As shown in Figures 9-13 and 9-14, eight degrees of ignition retard in diesel-fueled engines and five percent change in air-to-fuel ratios in gas-fueled engines yield about a 40 percent reduction in NO_x emissions. Consequently, in light of these limitations to the application of these emission control techniques, it is apparent that a 40-percent reduction in NO_x emissions is the most stringent regulatory option which could be selected as the basis for standards of performance. An alternative of 20 percent NO_x emission reductions was also considered a viable regulatory option which could serve as the basis for standards.

Environmental Impacts

Standards of performance based on alternative I (20-percent reduction) would reduce national NO_x emissions of about 14.6 million megagrams per year for all stationary sources by 72,500 megagrams annually in the fifth year after the standard went into effect. In contrast, standards of performance based on alternative II (40-percent reduction) would reduce national NO_x emissions by about 145,000 megagrams annually in the fifth year after the standard went into effect. Thus, standards of performance based on alternative II would have a much greater impact on national NO_x emissions than standards based on alternative I.

As discussed in Chapter 7, ambient air quality dispersion modeling, based on "worst case" conditions, indicates uncontrolled ambient air NO_x levels near large stationary internal combustion engines can vary from approximately 60 percent of the National Ambient Air Quality Standard of 100 $\mu g/m^3$ to over twice the standard depending on the size of the engine. One calculation for a large gas engine yielded an uncontrolled ambient NO_x level of about 220 $\mu g/m^3$.

These maximum concentrations, however, are located at distances extremely close to the source (0.3 km) because of the aerodynamic effects on plume rise as well as the relatively low height of the exhaust stack discharge. For example, it is estimated that at 1.0 km from the source, those concentrations would be only 15 percent of the above cited levels, well below the National Ambient Air Quality Standard.

In any event, standards of performance based on alternative I would reduce the highest calculated ambient air concentration of 220

$\mu g/m^3$ to about 180 $\mu g/m^3$, while standards based on alternative II would reduce this ambient NO_x concentration level to about 100 $\mu g/m^3$. Thus, where ambient air NO_x concentrations near large stationary internal combustion engines would be significant, standards of performance based on alternative II would be more effective in reducing ambient air NO_x levels than standards of performance based on alternative I.

Standards of performance based on either alternative would, with the exception of naturally aspirated gas engines, not significantly effect carbon monoxide (CO) or hydrocarbon (HC) emissions from most engines. A typical diesel engine with a sales-weighted average uncontrolled CO emission level of approximately 2.9 g/hp-hr would experience an increase in CO emissions of about 0.75 g/hp-hr (26 percent) to comply with standards of performance based on alternative I, and an increase of about 1.5 g/hp-hr (52 percent) to comply with standards of performance based on alternative II. Total hydrocarbon emissions would increase a sales-weighted average uncontrolled emission level of 0.3 g/hp-hr by about 0.06 g/hp-hr (20 percent) to comply with standards based on alternative I, and would increase by about 0.1 g/hp-hr (33 percent) to comply with standards of performance based on alternative II.

Similarly, a typical dual-fuel engine with a sales-weighted average uncontrolled CO emission level of approximately 2.7 g/hp-hr would experience an increase in CO emissions of about 1.2 g/hp-hr (44 percent) and about 2.7 g/hp-hr (100 percent) to comply with standards of performance based on alternatives I and II, respectively. Total hydrocarbon emissions, however, would decrease by about 0.3 g/hp-hr (11 percent) from a sales-weighted average uncontrolled level of a approximatley 2.8 g/hp-hr to comply with standards of performance based on alternative I. To comply with standards of performance based on alternative II total hydrocarbon emissions would decrease 0.6 g/hp-hr (21 percent).

A typical turbocharged or blower scavenged gas engine with a sales-weighted average uncontrolled CO emission level of approximately 7.7 g/hp-hr would experience an increase in CO emissions of about 1.9 g/hp-hr (25 percent) to comply with standards of performance based on alternative I and about 3.8 g/hp-hr (49 percent) to comply with standards of performance based on alternative II. Total hydrocarbon emissions would increase a sales-weighted average uncontrolled level of approximately 1.8 g/hp-hr by about 0.2 g/hp-hr (11 percent) to comply with standards of performance based on alternative I. To comply with standards of performance based on alternative II total hydrocarbon emissions would increase by about 0.4 g/hp-hr (22) percent.

A typical naturally aspirated gas engine with a sales-weighted average uncontrolled CO emission level of approximately 7.7 g/hp-hr would experience an increase in CO emissions of about 3.9 g/hp-hr (51 percent) to comply with standards of performance based on alternative I and about 17 g/hp-hr (220 percent) to comply with standards of performance based on alternative II. Total hydrocarbon emissions would increase a sales-weighted average uncontrolled level of approximately 1.8 g/hp-hr by about 0.04 g/hp-hr (2 percent) to comply with standards of performance based on alternative I. To comply with standards of performance based on alternative II total hydrocarbon emissions would increase by about 0.08 g/hp-hr (4 percent).

The increase in ambient air CO levels due to compliance with NO_x standards of performance based on either alternative would be small. For most engines, the application of standards of performance based on Alternative I would increase the maximum 8-hr ambient air CO concentration from about 0.23 mg/m^3 to 0.29 mg/m^3 for the typical diesel engine mentioned above. The application of standards of performance based on alternative II would increase the maximum 8-hour ambient air CO concentration to 0.35 mg/m^3. These values are insignificant compared to the National Ambient Air Quality Standard of 10 mg/m^3 for CO.

The application of standards of performance based on alternative I would increase the maximum 8-hr ambient air CO concentration from an uncontrolled concentration of 0.65 mg/m^3 to 0.94 mg/m^3 for the typical dual-fuel engine mentioned above. The application of standards of performance based on alternative II would increase the maximum 8-hr ambient air CO concentration to 1.3 mg/m^3.

For a typical turbocharged or blower scavenged gas engine, the increase in the maximum 8-hr ambient air CO concentration would be even less. The application of standards of performance based on alternative I would increase the maximum 8-hr ambient air CO concentration from an uncontrolled concentration of 0.15 mg/m^3 to 0.19 mg/m^3. The application of standards of performance based on alternative II would increase the maximum 8-hr ambient air CO concentration to 0.22 mg/m^3. These values are also insignificant compared to the National Ambient Air Quality Standard.

For a typical naturally aspirated gas engine, the application of standards of performance based on alternative I would increase the maximum 8-hr ambient air CO concentration from an uncontrolled concentration 0.77 mg/m^3 to 1.16 mg/m^3. The application of standards of performance based on alternative II would increase the maximum 8-hr ambient air CO concentration to approximately 2.0 mg/m^3.

Based on industry growth projections, an increase in national CO emissions of about 63,000 megagrams annually would be realized in the fifth year after the standards go into effect as a result of standards of performance based on alternative I. As a result of standards of performance based on alternative II an increase of about 216,000 megagrams annually would be realized in the fifth year after standards go into effect.

The large increase in CO emissions is due primarily to carbureted or naturally aspirated gas engines. These engines operate closer to stoichiometric conditions under which a small change in the air-to-fuel ratio results in a large increase in CO emissions. As shown in Figure 9-15, any significant NO_x reduction is accompanied by a significant increase in CO.

As discussed earlier, though the total national CO emissions would increase significantly, ambient air CO concentrations in the immediate vicinity of these carbureted or naturally aspirated gas engines would not be adversely affected. As a result of the standards of performance based on alternative II, the maximum 1 hour ground level concentration from a typical engine would increase to about 2 mg/m^3 compared to the National Ambient Air Quality Standard of 10 mg/m^3. Ambient air NO_x

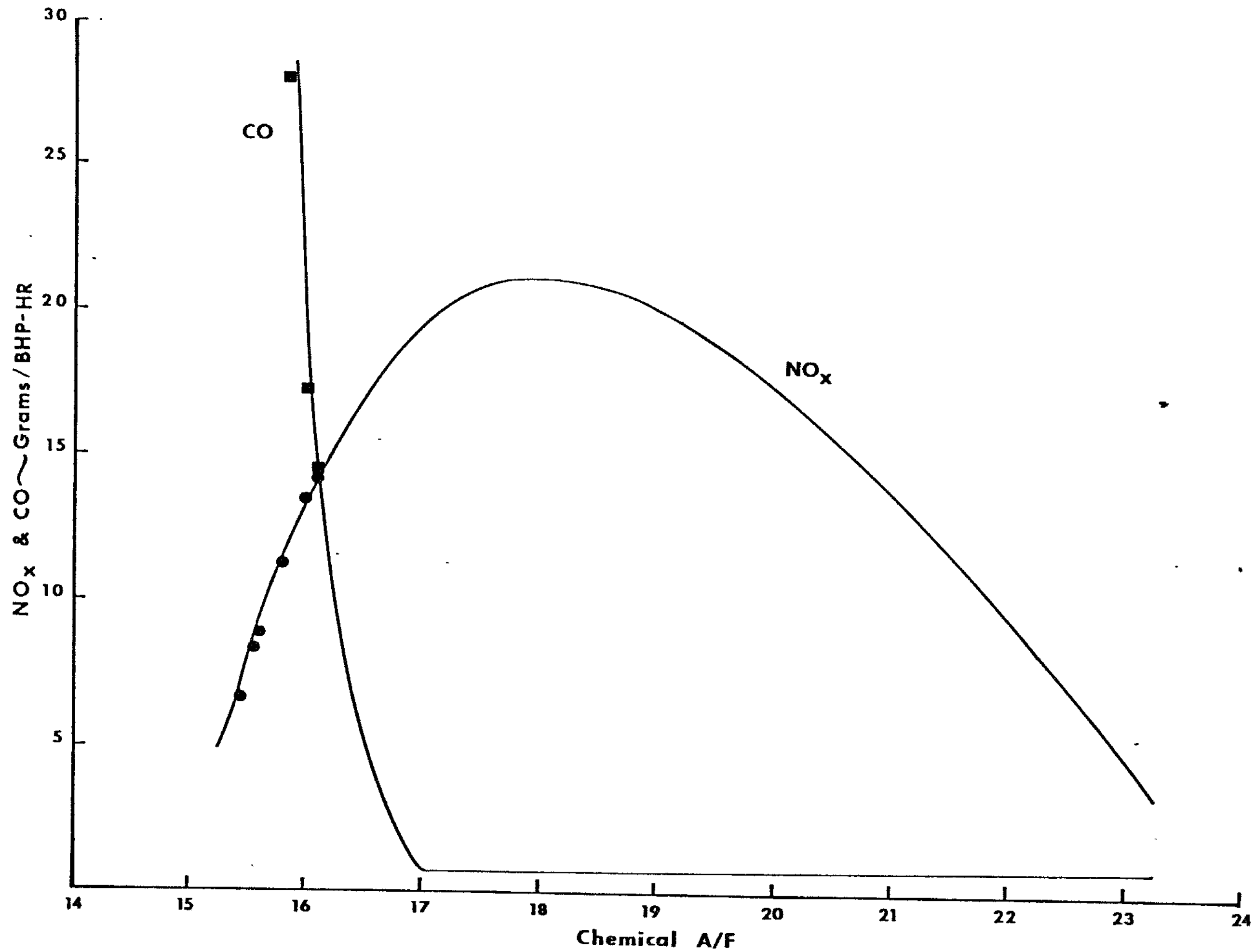


Figure 9-15. The effect of air-to-fuel ratio change on CO emissions from naturally aspirated gas engines.

concentrations from the same engine, however, would decrease concurrently about 40 percent, to a level less than half of the National Ambient Air Quality Standard of 100 $\mu g/m^3$.

Thus, there exists a trade-off between NO_x emissions reduction and CO emissions increase, particularly for carbureted or naturally aspirated gas engines. EPA recognizes this trade-off and is concerned about it's attractiveness. It should be noted though that CO emissions are a local problem since they rapidly oxidize to CO_2. Additionally, most naturally aspirated gas engines are operated in remote locations where CO is not a problem. NO_x emissions, however, are linked to the formation of photochemical oxidants and are subject to long range transport. NO_x emissions reductions are also much harder to achieve than CO or HC emissions reductions which may be achieved more easily from other sources.

One alternative is to propose a CO emissions limit based on the use of oxidizing catalysts. These catalysts can provide CO and HC emissions reductions on the order of 90 percent. Initial capital costs are high, however, averaging about $7500 for a typical 1000 horsepower naturally aspirated gas engine or about 15 percent of the purchase price of the engine.

EPA feels these costs for control of CO emissions are unreasonable. The trade-off between NO_x and CO emissions, however, seems reasonable. Therefore, CO was not selected for control by standards of performance.

Hydrocarbon emissions are also currently considered a pollutant of concern due to the impact on ambient air oxidant concentrations. However, although relationships are being developed to predict the HC emissions impact on oxidant concentrations, these concentrations depend on the ambient air NO_x/HC ratio. Thus, it is difficult to estimate the impact of increased HC emissions on ambient air oxidant concentrations. Furthermore, based on data in Appendix C.4, it is estimated that more than 90 percent of the total hydrocarbon emissions from gas engines and 75 percent of the total hydrocarbons from dual-fuel engines are methane, which is nonreactive and does not lead to oxidant formation. Finally, the increase in national total HC emissions based on either alternative, for most engines, is very small.

Standards of performance based on alternative I would increase national total HC emissions of 10.2 million megagrams by about 2,300 megagrams annually in the fifth year after the standards went into effect compared to an increase of about 4,600 megagrams annually associated with alternative II. Standards of performance based on alternative I would increase national reactive HC emissions by approximately 108 megagrams annually in the fifth year after the standards went into effect, compared to an increase of approximately 216 megagrams annually associated with alternative II.

As described in Chapter 3, stationary internal combustion engines are sources of NO_x, HC and CO emissions, with both NO_x and HC contributing to oxidant formation. With regard to regulation of emission from IC engines, NO_x emissions are of more concern than emissions of hydrocarbons for two reasons. First, NO_x is emitted in greater quantities from stationary internal combustion engines than hydrocarbons. Second, a high priority has been assigned to development of standards of performance limiting NO_x emissions from stationary sources are projected to increase by more than 40 percent in the 1975-to-1990 period. Applying best technology to all new sources would reduce this increase but would not prevent it from occurring. This unavoidable increase in NO_x emissions is attributable largely to the fact that current NO_x emission control techniques are based on combustion redesign. In addition, few NO_x emission control techniques can achieve large (i.e., in the range of 90 percent) reductions in NO_x emissions. In contrast, HC emissions are much easier to reduce. Large reductions from numerous sources are achievable with the installation of existing add-on control equipment. Consequently, EPA has assigned a high priority to the development of standards of performance for major NO_x emission sources wherever significant reductions in NO_x can be achieved.

The slight increase in HC emissions from IC engines associated with control of NO_x from IC engines can be offset from other sources easier than NO_x emissions can be reduced from other sources. Therefore, the adverse environmental impact of increased HC emissions due to the reduction in NO_x emissions is considered small.

There would be essentially no water pollution impact of standards of performance based on either alternative I or alternative II. Only one control technique, increased manifold air cooling, could result in an additional discharge of water. However, most newly installed engines use a closed cooling system with no water discharge.

Standards of performance based on either alternative would also have no solid waste impact.

There would also be no adverse noise impact resulting from standards of performance based on either alternative. Fan noise levels from large-bore stationary engine installations could increase slightly as a result of increased cooling requirements; however, in typical installations such as municipal generator plants, pipeline compressor stations or industrial process plants, such increases are insignificant in comparison to existing noise levels.

Thus, as reflected in the summary Table 9-6, the environmental impacts of standards of performance based on either alternative are small and reasonable.

Energy Impacts

The potential energy impact of standards of performance based on either alternative is small. As discussed in Section 6.2, standards of performance based on alternative I could increase the fuel consumption of a typical blower scavenged or turbocharged gas engine by approximately one percent, whereas standards of performance based on alternative II could increase the fuel consumption by approximately two percent. A typical 2000 horsepower blower scavenged or turbocharged gas engine has an uncontrolled fuel consumption of approximately 343,000 scf natural gas per day (the energy equivalent of 2842 gallons oil per day). Increases translate into actual increased fuel consumption of approximately 3500 scf and 7000 scf natural gas per day (the energy equivalent of 25 and 50 gallons oil per day).

Standards of performance based on alternative I would increase the fuel consumption of a typical naturally aspirated gas engine by approximately six percent. Standards of performance based on alternative II, however, would increase the fuel consumption by approximately eight percent.

A typical 2000 horsepower naturally aspirated gas engine has an

Table 9-6 ENVIRONMENTAL IMPACTS OF ALTERNATIVES

Pollutant	Base Level[a]	Alternative I	Alternative II
National NO_x Emissions	14.6×10^6 megagrams	Reduced by 72,500 megagrams annually 5 years after standard goes into effect	Reduced by 145,000 megagrams annually 5 years after standard goes into effect
National CO Emissions	33.0×10^6 megagrams	Increased by 63,000 megagrams annually 5 years after standard goes into effect	Increased by 216,000 megagrams annually 5 years after standard goes into effect
National Total HC Emissions	10.2×10^6 megagrams	Total Hydrocarbons Increased by 2,300 megagrams annually 5 years after standard goes into effect Reactive Hydrocarbons Increased by 108 megagrams annually 5 years after standard goes into effect	Total Hydrocarbons Increased by 4,600 megagrams annually 5 years after standard goes into effect Reactive Hydrocarbons Increased by 216 megagrams annually 5 years after standard goes into effect
Water Pollution	--	No increase	No increase
Solid Waste	--	No increase	No increase
Noise	--	No adverse impact	No adverse impact

[a]Total U.S. emission from stationary sources as per EPA Nationwide Air Pollutant Inventory for 1975

uncontrolled fuel consumption of approximately 343,000 scf natural gas per day (the energy equivalent of 2842 gallons oil per day).

These percentage increases represent actual fuel consumption increases of about 20,600 and 27,400 scf natural gas per day (the energy equivalent of 142 and 189 gallons oil per day).

Standards of performance based on alternative I could increase the fuel consumption of a typical dual-fuel engine by approximately one percent, whereas standards of performance based on alternative II could increase the fuel consumption by approximately three percent. A typical dual-fuel engine rated at 2000 horsepower has an uncontrolled fuel consumption of approximately 297,000 scf natural gas per day (the energy equivalent of 2150 gallons oil per day). These percentage increases represent an actual fuel consumption increase of about 6100 and 12,200 scf natural gas per day (the energy equivalent of 43 and 86 gallons oil per day).

Standards of performance based on alternative I could increase the fuel consumption of a typical diesel engine by approximately three percent, whereas standards of performance based on alternative II could increase the fuel consumption by approximately seven percent. For a typical diesel engine rated at 2000 horsepower, with an uncontrolled fuel consumption of approximately 2320 gallons of oil per day, these percentage increases represent actual fuel consumption increases of about 70 and 160 gallons of oil per day.

Thus, the potential energy impact in the fifth year after the standard goes into effect, based on alternative I, would be equivalent to approximately 1.03 million barrels of oil per year compared to an uncontrolled fuel consumption of IC engines affected by the standard of 31 million barrels per year. The potential energy impact in the fifth year after the standard goes into effect, based on alternative II, would be equivalent to approximately 1.5 million barrels of oil per year.

It should be noted that the largest increase represents only 0.01 percent of the 1977 domestic consumption of crude oil and natural gas. The largest increase also represents only 0.03 percent of the projected total oil imported to the United States five years after the standards go into effect.

Thus, as reflected in the summary Table 9-7, the energy impacts of standards of performance based on either alternative are small and reasonable.

TABLE 9-7. ENERGY IMPACTS OF ALTERNATIVES

Engine Fuel Type	Uncontrolled[a] Fuel Consumption (gal/day)	Increase in Fuel Consumption (gal/day)	
		Alternative I	Alternative II
Gas[b]	2842[d]	25	50
Gas[c]	2842	142	189
Dual Fuel	2151	43	86
Diesel	2317	70	162
Totals of all new engines after 5 years	31,000,000 bbls oil/yr	1.03 million bbls oil/yr	1.5 million bbls oil/yr

[a] Typical 2000 horsepower engine
[b] Blower scavenged or turbocharged
[c] Naturally aspirated
[d] Expressed as equivalent oil consumption

Economic Impact of Alternatives

Manufacturers of stationary internal combustion engines would incur additional costs due to standards of performance. These costs however would be small. As discussed in Section 6.3, these costs are a result of one or more of the following activities that may be needed to manufacture engines which meet standards of performance: (1) extended testing to verify the effectiveness of a particular control approach; (2) development and application of NO_x controls to existing engine designs; and (3) engineering, tooling and pattern costs for minor redesign of an engine family to accomodate application of a control technique. It is estimated that the total costs to the manufacturer for each engine model family, including development, durability tests, and retooling, would be approximately: (1) $125,000 for retard and air-to-fuel change; (2) $150,000 for manifold air temperature reduction; and (3) $25,000 for derate. For each manufacturer, therefore, total costs would vary depending on (1) the number of engine model families produced, (2) their degree of advancement in emission testing, (3) the uncontrolled emission levels of their engines, (4) the development and durability testing required to produce engines that can meet proposed standards of performance, and (5) the emission control technique selected.

As reported in Section 8.4, the economic impacts on manufacturers arising from these cost penalties associated with standards of performance based on either alternative would be small.

The manufacturer's total capital investment requirements for developmental testing of engine models is estimated to be about $4.5 million to comply with standards of performance based on alternative I and about $5 million to comply with standards of performance based on alternative II. These expenditures would be made over a two year period. Analysis of the financial statements of engine manufacturers or their parent companies indicates that the manufacturers' overhead budgets are sufficient to support the development of these controls without adverse impact on their financial position.

As discussed in Section 8.4.1.2, manufacturers would not experience significant differential cost impacts among competing engine model families. The cost penalties summarized in Table 8-16 reflect the range of total annualized cost penalties to the end use applications for each engine fuel type and manufacture for each alternative. These costs for each major end use, the cross-price inelasticities, and the importance of each end use market to the companies' total internal combustion sales were analyzed to determine the relative sales advantages between companies. Consequently, these analyses indicated that no significant sales advantages or disadvantages would develop among competing manufacturers for standards of performance based on either alternative. Based on "worst case" assumptions the maximum intra-industry sales losses would be about six percent as a result of standards of performance based on either alternative. Thus, the intra-industry impacts would be moderate and not cause any major dislocations within the industry.

These total annualized cost penalties imposed on IC engines by standards of performance would also have very little impact with regard to increasing sales of gas turbines. Turbines do not compete with internal combustion engines based on annualized costs alone, due to their higher operating costs (fuel). As discussed in Subsection 8.4.1.3, the total annualized cost penalty associated with standards of performance based on either alternative would bring the cost of owning internal combustion engines up to that of turbines in only one case -- diesel internal combustion engines used in electric generation. This conclusion, however, is based on limited data. It is quite likely, however, that this manufacturer's line of diesel engines, through minor combustion modifications, could reduce their NO_x emission to levels comparable to that of other manufacturers. Further, due to technical limitations, economic considerations, and customer preference, it is unlikely that IC engine users will switch to gas turbines. For example, it is unlikely that turbines would replace diesel engines in plants using banks of smaller engines, unless the entire bank were replaced with one turbine.

Standards of performance based on alternative I would result in no loss of sales to gas turbines whereas standards of performance based on alternative II would result in the possible loss of sales for one diesel manufacturer.

Thus, the economic impacts on the manufacturers arising from standards of performance based on either alternative are considered small and reasonable.

The application of NO_x controls will also increase costs to the engine user. The magnitude of this increase will depend upon the amount and type of emission control applied. As was shown in Section 6.3, various control approaches affect initial costs, fuel consumption, and maintenance differently. Fuel penalites, though, are the major factor affecting this increase for high usage engines.

The following four end uses were selected to represent the major applications of diesel, dual-fuel, and natural gas engines: (1) diesel engine, electrical generation; (2) dual-fuel engine, electrical generation, (3) gas engine, oil and gas transmission and (4) gas engine, oil and gas production.

The total annualized cost of a typical uncontrolled diesel fuel, electrical generation engine is about 2.5¢/hp-hr. For a typical 2000 horsepower engine operating 8000 hours per year, this total annualized cost would be about $450,000 per year. Standards of performance based on alternative I would increase this total annualized cost by about 0.04¢/hp-hr (1.5 percent). Similarly, standards of performance based on alternative II would increase the total annualized cost by about 0.11¢/hp-hr (4.5 percent). For the engine mentioned above, these values translate into dollar amounts of about $6,400 and $17,600 respectively.

The total annualized cost of a typical uncontrolled dual-fuel, electrical generation engine is about 2.8¢/hp-hr. For a typical 2000 horsepower engine operating 8000 hours per year this would be about $448,000 per year. As a result of standards of performance based on alternative I this total annualized cost would increase by about 0.07¢/hp-hr (2.5 percent). As a result of standards of performance based on alternative II, this total annualized cost would increase by about 0.09¢/hp-hr (3.2 percent). For this engine these values translate into dollar amounts of about $11,200 and $14,400 respectively.

The total annualized cost of a typical uncontrolled natural gas fuel, oil and gas transmission engine is about 2.2¢/hp-hr. For a typical 2000 horsepower engine operating 8000 hours per year, this total annualized cost would be about $354,000 per year. Standards of performance based on alternative I would increase this total annualized cost by about 0.02¢/hp-hr (1 percent). Standards of performance based on alternative II would increase the total annualized cost by about 0.04¢/hp-hr (2 percent). For the engine mentioned above, these values translate into dollar amounts of about $3500 and $7100, respectively.

The total annualized cost of a typical uncontrolled natural gas fuel, oil and gas production engine is about 2.2¢/hp-hr. For a typical 2000 horsepower engine operating 8000 hours per year, this total annualized cost would be about $250,000 per year. Standards of performance based on alternative I would increase this total annualized cost by about 0.14¢/hp-hr (6.1 percent). Standards of performance based on alternative II would increase this total annualized cost by about 0.16¢/hp-hr (8 percent). For the typical engine mentioned above, these values translate into dollar amounts of about $22,400 and $25,600, respectively.

Total uncontrolled annualized costs of $580 million by all large stationary internal combustion engine users would increase by about $25 million to comply with standards of performance based on alternative I and by about $32 million to comply with standards of performance based on alternative II in the fifth year after standards go into effect.

The manufacturer's capital test requirements would be regarded as an added expense and most likely passed on to the engine users in the form of higher prices. Therefore, users of internal combustion engines would have to expend additional capital to purchase more expensive engines. This capital cost penalty however, is small. A two percent increase in engine price would be expected on the average as a result of standards of performance based on either alternative. Typical initial costs for uncontrolled diesel and dual-fuel, electrical generation engines, and natural gas, oil and gas transmission engines are about \$150/hp-hr. Initial costs for natural gas fuel, oil and gas production engines are about \$50/hp. For typical 2000 horsepower engines, these initial capital costs would be about \$300,000 and \$100,000, respectively.

Standards of performance based on either alternative would increase the initial capital cost of a typical diesel or dual-fuel, electrical generation engine or natural gas fuel, oil and gas transmission engine rated at 2000 horsepower by about \$6000.

In contrast, standards of performance based on either alternative would increase the initial capital cost of a typical natural gas, oil and gas production engine rated at 2000 horsepower by about \$2000.

The total additional capital cost for all users would equal about \$9.6 million per year on a cumulative basis on either alternative compared to total uncontrolled costs of all new engines of \$450 million per year.

As discussed in Section 8.4, the economic impacts on users arising from the cost penalties associated with standards of performance based on either alternative would be small. In general, these impacts translate into price increases for the end products or services provided by the industrial and commercial users of large stationary internal combustion engines. The electric utility industry would realize a price increase after five years of 0.02 percent to comply with standards of performance based on either alternative. After five years, delivered natural gas prices would increase 0.02 percent due to the application standards of performance based on alternative I and 0.04 percent due to the application standards of performance based on alternative II.

Even after a full phase-in period of 30 years, during which new controlled engines would replace all existing uncontrolled engines, the electric utility industry would realize a price increase of only 0.1 percent to comply with standards of performance based on either alternative. Similarly, delivered natural gas prices would increase only 0.1 percent due to the application of standards of performance based on alternative I and 0.3 percent to comply with standards of performance based on alternative II. Thus, the economic impacts of standards of performance based on either alternative are considered small and reasonable.

Conclusions

Based on this assessment of the impacts of each alternative, and given the fact that alternative II achieves a greater degree of NO_x reduction, it is selected as the best technological system of continuous emission reduction of NO_x from stationary large-bore IC engines considering the cost of achieving such emission reduction, any nonair quality health and environmental impact and energy requirements.

Table 9-8, which follows, summarizes the economic impacts of each alternative.

TABLE 9-8 ECONOMIC IMPACTS OF ALTERNATIVES

Impact	Uncontrolled Level of Cost	Alternative I	Alternative II
<u>Impact on Manufacturer</u>			
Capital budget requirements	--	$4.5 million over two years; able to generate internally from profits.	$5 million over two years; able to generate internally from profits.
Intra-industry competition	--	Maximum sales loss unlikely to exceed 6% of internal combustion engine sales for any firm.	6% maximum loss for any firm
Competition from gas turbines	--	No losses.	Possible sales loss for one diesel manufacturer.
<u>Impact on End-Use Applications</u>			
Total annualized cost[a]			
Diesel fuel, electrical generation	2.5¢/hp-hr	Base increased by 0.04¢/hp-hr	Increased by 0.11¢/hp-hr
Dual-fuel, electrical generation	2.8¢/hp-hr	Increased by 0.07¢/hp-hr	Increased by 0.09¢/hp-hr
Natural gas fuel, oil and gas transmission	2.2¢/hp-hr	Increased by 0.02¢/hp-hr	Increased by 0.04¢/hp-hr
Natural gas fuel, oil and gas production	2.2¢/hp-hr	Increased by 0.14¢/hp-hr	Increased by 0.16¢/hp-hr
Totals of all new engines after 5 years	$580 million	Increased by $25 million	Increased by $32 million
Capital Cost Penalty[a]			
Diesel fuel, electrical generation or dual fuel, electrical generation or natural gas fuel, oil and gas transmission	$150/hp	Increased by $3.00/hp	Increased by $3.00/hp
Natural gas fuel, oil and gas production	$ 50/hp	Increased by $1.00/hp	Increased by $1.00/hp
Totals etc.	$450 million	$9.6 million on a cumulative basis over first 5 years after standards go into effect.	$9.6 million on a cumulative basis over first 5 years after standards go into effect.
<u>Impact on Product Prices and Users</u>			
Electricity prices	--	U.S. electric bill up 0.02% after 5 years. U.S. electric bill up 0.1% after full phase-in.	U.S. electric bill up 0.02% after 5 years. U.S. electric bill up 0.1% after full phase-in[b].
Gas prices	--	Delivered natural gas prices up 0.02% after 5 years. Delivered natural gas prices up 0.1% after full phasein.	Delivered natural gas prices up 0.04% after 5 years. Delivered natural gas prices up 0.3% full phasein.

[a]Assumed typical 2000 horsepower engine operating 8000 hours per year in all cases
[b]Full phase-in implies replacement of all existing engines

9.5 SELECTION OF FORMAT FOR THE STANDARDS

A number of different formats could be used to limit NO_x emissions from large stationary internal combustion engines. Standards could be developed to limit emissions in terms of: (1) percent reduction, (2) mass emission per unit of energy (power) output, (3) mass emissions per unit of energy (fuel) input, or (4) concentration of emissions in the exhaust gases discharged to the atmosphere.

Analysis of the effectiveness of the various demonstrated NO_x emission control techniques clearly shows that what is demonstrated is the ability to achieve a percent reduction in NO_x emissions. In other words, application of each emission control technique to the same degree (i.e., eight degrees of ignition retard to five percent change in air-to-fuel ratios) will result in essentially the same percentage reduction in NO_x emissions. However, a percent reduction format is highly impractical for two reasons. First a reference uncontrolled NO_x emission level would have to be established for each manufacturer's engine, a difficult task since some manufacturers produce as many as 25 models which are sold with several ratings. Second, a reference uncontrolled NO_x emission level would have to be established for any new engines developed after promulgation of the standard. This would be quite simple for engines that employed NO_x control techniques such as ignition retard or air-to-fuel ratio change to comply with standards. Emissions could be measured without the use of these techniques. For engines designed to comply with the standards through the use of combustion chamber modification, however, this would not be possible. Thus, new engines would receive no credit for the NO_x emission reduction achieved by combustion chamber redesign.

A mass-per-unit-of-energy-output format, typically referred to as brake-specific emissions (g/hp-hr), relates the total mass of NO_x emissions to the engine's productivity. Although brake-specific mass standards (g/hp-hr) appear meaningful because they relate directly to the quantity of emissions discharges into the atmosphere, there are disadvantages in that enforcement of mass standards would be costly and complicated in practice. This can be illustrated by examining the relationship between brake-specific mass emissions ($BSNO_x$) and the parameters that would have to be measured in the field:

$$BSNO_x \sim NO_x\ (m_e)\ (1/w)$$

where:

$BSNO_x$ = grams NO_x/horsepower-hour

NO_x = concentration of NO_x in exhaust, parts per million (ppm)

m_e = exhaust mass flowrate, lb/hr

w = power output, horsepower

Thus, exhaust flow and power output would have to be determined in addition to NO_x concentration. For example, to determine exhaust gas flowrate, one of three methods can be used: (1) directly measure exhaust volume flowrate: (2) measure inlet air and fuel flowrate; and (3) measure all exhaust carbon constituents (primarily HC, CO, CO_2), and fuel flow, and conduct a fuel analysis.

Since large internal combustion engines have very large exhaust flowrates (in excess of 50,000 cfm), exhaust flowrates are difficult to determine accurately in either the field or laboratory. Similarly, the accurate measurement of inlet airflow is difficult. Thus, methods (1) or (2) are unlikely to be used in practice for large engines.

Although method (3) has been used in the field to determine brake-specific mass emissions, the measurement of three additional exhaust gas constituents and the fuel analysis considerably complicate the test procedure[31]. Moreover, it is difficult to accurately measure fuel flow over a short interval (typically less than 1/2 hour, which would be required for a performance test). Thus, the determination of exhaust gas flowrates in the field is difficult and complicated.

Another disadvantage of the brake-specific mass emissions format is that power output must be determined. Power can be determined from an engine dynamometer in the laboratory, but dynamometers cannot be used in the field. Power output could be determined by: (1) inferring the power from engine operating parameters (fuel flow, rpm, manifold pressure, etc.) or (2) inferring engine power from the output of the generator or compressor attached to the engine. In practice, however, these approaches are time consuming and are less accurate than dynamometer measurements.

A format limiting NO_x emissions per unit of energy (fuel) input would be specified in terms of grams NO_x per joule fuel input (equivalent to lb NO_x/M Btu). The advantage of this format is that no power measurement would be required, thereby simplifying enforcement. However, as with a brake-specific mass emission format, total exhaust gas mass flowrates must be calculated, and as was discussed earlier, all methods for this determination are difficult under field conditions.

In addition, standards of performance based on fuel input could penalize more efficient engines, which typically operate at higher temperatures and pressures, leading to higher NO_x emissions. For example, given two engines with the same brake-specific emissions, the more efficient engine, which consumes less fuel, will have a higher fuel-based emissions level because the ratio of mass NO_x emissions per unit of fuel energy input has a smaller denominator. Thus, this format could offset other incentives manufacturers have to develop more efficient engines.

Another possible format would be to limit the concentration of NO_x emissions in the exhaust gases discharged to the atmosphere. Concentrations would be specifed in terms of parts of NO_x per million (ppm) parts of exhaust (volumetric). The major advantage of this format is in the simplicity of its enforcement. As compared to the formats discussed previously, only a minimum of data and calculations are required, which decreases testing costs and minimizes errors in determining compliance with an emission standard. Measurements are direct; only NO_x and O_2 concentration measurements of exhaust gas must be made. The NO_x measurement reads out directly in ppm of dry exhaust, and the oxygen measurement, required to prevent a user from diluting the exhaust gas with air and lowering the NO_x concentration, reads out in percent-O_2. A reference concentration of oxygen, however, must be established for this format.

The primary disadvantages associated with concentration standards are: (1) a standard could be circumvented by dilution of exhaust gases discharged into the atmosphere, which lowers the concentration of the emissions but does not reduce the total mass emitted, and (2) a concentration standard could penalize high efficiency engines because more efficient engines generally discharge higher concentrations of NO_x

emissions due to higher operating temperatures and pressures as mentioned above (although the mass emission rate may be the same as a lower efficiency engine). A concentration standard based on low efficiency engines, therefore, could penalize high efficiency engines. Both these problems, however, can be overcome through the use of appropriate "correction" factors.

Since the percent reduction format is impractical, and the problems associated with the enforcement of mass standards (mass per unit energy output or input) appear to outweigh the benefits, the concentration formation was selected as the format for standards of performance for large stationary internal combustion engines.

As mentioned above, because a concentration standard can be circumvented by dilution of the exhaust gases, measured concentrations must be expressed relative to some fixed dilution level. For combustion processes, this can be accomplished by correcting measured concentrations to a reference concentration of oxygen. The oxygen concentration in the exhaust gases is related to the excess (or dilution) air. Typical oxygen concentrations in large-bore internal combustion engines can range from 8 to 16 percent but are normally about 15 percent. Thus, referencing the standard to a typical level of 15 percent oxygen would prevent circumvention by dilution. (Section 9.6 discusses the correction factor for adjusting measured NO_x concentrations to an oxygen concentration of 15 percent).

As also mentioned above, selection of a concentration format could penalize high efficiency internal combustion engines. These highly efficient engines generally operate at higher temperatures and pressures, and as a result discharge gases with higher NO_x concentrations than less efficient engines, although both engines' brake-specific mass emissions could be the same. Thus, a concentration standard based on low efficiency engines could effectively require more stringent controls for high efficiency engines. Conversely, a concentration standard based on high efficiency engines would require no controls. Consequently, selecting a concentration format for standards of performance requires an efficiency factor to permit higher NO_x emission from more efficient engines.

The incentive for manufacturers to increase engine efficiency is to lower engine fuel consumption. Therefore, the objective of an efficiency adjustment factor should be to give an emissions credit for the lower fuel consumption of more efficient internal combustion engines. Since the fuel consumption of internal combustion engines varies linearly with efficiency, a linear adjustment factor is selected to permit increased NO_x emissions from highly efficient internal combustion engines. A linear efficiency adjustment factor also effectively limits NO_x emissions to a constant mass emission rate per unit of power output.

The efficiency adjustment factor needs to be referenced to a baseline efficiency. Most large existing stationary internal combustion engines fall in the range of 30 to 40 percent efficiency. Therefore, 35 percent is selected as the baseline efficiency. The efficiency of internal combustion engines is usually expressed in terms of heat rate. The heat rate of engines operating at 35 percent efficiency is about 7270 Btu/hp-hr. Thus, the following linear adjustment factor is selected to permit increased NO_x emissions from high efficiency large stationary internal combustion engines:

$$X_a = X \frac{7270}{Y}$$

where:

X_a = Adjusted NO_x emissions permitted at 15 percent oxygen, ppmv

X = NO_x emission limit specified in the standards at 15 percent oxygen on a dry basis

Y = LHV heat input per unit of power output (Btu/hp-hr)

NOTE: Above adjustment is made at standard atmospheric conditions of 29.92 m Hg, 85°F, and 75 grains moisture per pound of dry air.

This efficiency adjustment factor permits a linear increase in NO_x emission with increased efficiencies above 35 percent. This adjustment would not be used to adjust the emission limit downward for internal combustion engines with efficiencies of less than 35 percent. This efficiency adjustment factor also applies only to the IC engine itself and not the entire system of which the engine may be a part. Since Section 111 of the Clean Air Act requires the use of the best system of emission reduction in all cases, this precludes the application of the efficiency adjustment factor to an entire system. For example, IC engines with waste heat recovery may have a higher overall efficiency than the IC engine alone. Thus, the application of the efficiency adjustment factor to the entire system would permit greater NO_x emissions because of the system's higher overall efficiency, and would not necessarily require the use of the best demonstrated system of emission reduction on the IC engine.

9.6 SELECTION OF NUMERICAL EMISSION LIMITS

Overall Approach

As mentioned earlier, it is difficult to select a specific NO_x emission limit which all IC engines could meet primarily through the use of ignition retard or air-to-fuel ratio change. Because of inherent differences among various IC engines with regard to uncontrolled NO_x emission levels, there exists a rather large variation within the data and information included in the SSEIS concerning controlled NO_x emission levels. Generally speaking, engines with relatively low uncontrolled NO_x emissions achieved low controlled NO_x emission levels, and engines with high uncontrolled NO_x emission levels achieved relatively high controlled NO_x emission levels. Consequently, the following alternatives were considered for selection of the numerical concentration emission limits based on a 40 percent reduction in NO_x emissions:

1. Apply the 40 percent reduction to the highest observed uncontrolled NO_x emission level.
2. Apply the 40 percent reduction to a sales-weighted average uncontrolled NO_x emission level.
3. Apply the 40 percent reduction to this sales-weighted average uncontrolled NO_x emission level plus one standard deviation.

The highest observed uncontrolled NO_x emission levels for diesel, dual-fuel and gas engines discussed in alternative I above can be found in Figures 4-49(a-c), respectively. The uncontrolled levels for dual-fuel engines are generally lower than those for diesels, which are generally lower than those for gas engines. The highest uncontrolled levels for each fuel type are as follows: (1) gas, 29 g/hp-hr, (2) dual-fuel, 15.0 g/hp-hr, and (3) diesel, 19 g/hp-hr.

The sales-weighted uncontrolled NO_x emission levels which are used as the base levels in the second alternative are discussed in Section 4.3.4. It was noted that uncontrolled NO_x emission levels vary among both engines of the same fuel type and of different fuels (even after considering the effects of ambient conditions and measurement methods). Therefore, an average uncontrolled level was determined by applying a sales-weighting to each manufacturer's average uncontrolled NO_x emissions for engines of each fuel type (see Section 4.3.4). The sales-weighting, based on horsepower sold, gives more weight to those engine models which have the highest sales. The sales-weighted average uncontrolled NO_x emission level for each engine fuel type are as follows: (1) gas, 15 g/hp-hr, (2) dual-fuel, 8 g/hp-hr, and (3) diesel, 11 g/hp-hr.

The third alternative incorporates a "margin for engine variability" by adding one standard deviation to the sales-weighted average uncontrolled NO_x emission level and then applying the 40 percent reduction. Standard deviations discussed were calculated from the uncontrolled NO_x emission data included in the SSEIS, assuming it had a normal distribution. A subsequent statistical evaluation of the data indicated that this assumption was valid (see Appendix C for a complete discussion). The standard deviations for each engine fuel type are as follows: (1) gas, 4 g/hp-hr, (2) dual-fuel, 3.2 g/hp-hr and (3) diesel, 3.7 g/hp-hr.

The standard deviation of the uncontrolled NO_x emission data base is relatively large compared to the sales-weighted average uncontrolled internal combustion engines:

$$X_a = X \quad \frac{7270}{Y}$$

where:

X_a = Adjusted NO_x emissions permitted at 15 percent oxygen, ppmv

X = NO_x emission limit specified in the standards at 15 percent oxygen on a dry basis

Y = LHV heat input per unit of power output (Btu/hp-hr)

NOTE: Above adjustment is made at standard atmospheric conditions of 29.92 m Hg, 85°F, and 75 grains moisture per pound of dry air.

This efficiency adjustment factor permits a linear increase in NO_x emission with increased efficiencies above 35 percent. This adjustment would not be used to adjust the emission limit downward for internal combustion engines with efficiencies of less than 35 percent. This efficiency adjustment factor also applies only to the IC engine itself and not the entire system of which the engine may be a part. Since Section 111 of the Clean Air Act requires the use of the best system of emission reduction in all cases, this precludes the application of the efficiency adjustment factor to an entire system. For example, IC engines with waste heat recovery may have a higher overall efficiency than the IC engine alone. Thus, the application of the efficiency adjustment factor to the entire system would permit greater NO_x emissions because of the system's higher overall efficiency, and would not necessarily require the use of the best demonstrated system of emission reduction on the IC engine.

concentration emission limit.

The first alternative is to apply the 40 percent reduction to the highest uncontrolled NO_x emission level within a fuel category. For example, Figure 4-49(c), which summarizes NO_x emission reductions achieved by gas engines, lists 29 g/hp-hr as the highest uncontrolled NO_x emission level. The application of a 40 percent reduction would lead to an emission level of about 17 g/hp-hr. As illustrated in Figure 9-16, if this level were selected as a standard of performance, 99 percent of production gas engines could easily meet the emission limit by reducing emissions by 40 percent or less. However, 69 percent of production engines would not have to reduce NO_x emissions at all. Only one percent of production engines would have to reduce NO_x emissions by more than 40 percent.

The second alternative is to apply the 40 percent reduction to the sales-weighted average uncontrolled NO_x emission level. For example, the sales-weighted average uncontrolled NO_x level for gas engines is 15 g/hp-hr. The application of a 40 percent reduction would lead to an NO_x emission level of 9 g/hp-hr. As illustrated in Figure 9-16, if this level were selected as a standard of performance, 50 percent of production gas engines could meet the standard with 40 percent or less reduction in NO_x emissions. However, 50 percent of production gas engines would be required to reduce NO_x emission by greater than 40 percent. Only seven percent of production gas engines would not have to reduce NO_x emissions at all.

The third alternative is to base the standard on a 40 percent reduction in NO_x emissions from the sales-weighted average uncontrolled NO_x emission level plus one standard deviation. For example, the sales-weighted average uncontrolled NO_x emission level for gas production gas engines is 15 g/hp-hr and the standard deviation of the production gas engine data base (Appendix C) is 4 g/hp-hr. Thus, the application of a 40 percent reduction to the sum of these two values would lead to an emission level of 11 g/hp-hr. As illustrated in Figure 9-16, if this level were selected as a standard of performance, 84 percent of the production gas engines would not have to reduce NO_x emission at all. Only 16 percent of the production gas engines would have to reduce NO_x emissions by more than 40 percent.

Similarly, applying the three alternatives to dual-fuel engines yields results similar to those for gas engines. The highest uncontrolled NO_x emission level from a dual fuel engine is 15 g/hp-hr. The application of a 40 percent reduction would lead to an emission level of 9 g/hp-hr. If this level were selected as a standard of performance, 98 percent of production dual-fuel engines could easily meet the emission limit by reducing NO_x emissions by 40 percent or less. However, 62 percent would have to achieve no reduction in NO_x emissions. Only two percent of production engines would have to reduce NO_x emissions by more than 40 percent.

The sales-weighted average uncontrolled NO_x emission level for dual-fuel engines is 8 g/hp-hr. The application of a 40 percent reduction would lead to a NO_x emission level of about 5 g/hp-hr. If this level were selected as a standard of performance, 54 percent of the production dual-fuel engines could meet the standard by reducing NO_x emissions 40 percent or less. Only 18 percent of the production dual-fuel engines would not have to reduce NO_x emissions at all. Also, 46 percent of the production dual-fuel engines would be required to reduce NO_x emissions by greater than 40 percent.

The standard deviation of the production dual-fuel engine data base is 3.2 g/hp-hr. Thus, the application of a 40 percent reduction to the sum of the sales-weighted average uncontrolled NO_x emission level (8 g/hp-hr) and the standard deviation (3.2 g/hp-hr) would lead to an emission level of 7 g/hp-hr. If this level were selected as a standard of performance, 87 percent of the production dual-fuel engines could easily meet the emission limit by reducing emissions by 40 percent or less. However, 48 percent of the production gas engines would not have to reduce NO_x emission at all. Only 13 percent of the production gas engines would have to reduce NO_x emissions by more than 40 percent.

Finally, the application of the three alternatives to diesel engines also yields very similar results. The highest uncontrolled NO_x emission level from a diesel engine is 19 g/hp-hr. The application of a 40 percent reduction would lead to in an emission level of about 11 g/hp-hr. If this level were selected as a standard of performance, 98 percent of production diesel engines could easily meet the emission limit by reducing emissions by 40 percent or less. However, 40 percent would have to achieve no reduction in NO_x emissions. Two percent of production engines would be required to reduce NO_x emission by more than 40 percent.

The sales-weighted average uncontrolled NO_x emission level for diesel engines is 11 g/hp-hr. The application of a 40 percent reduction would lead to a NO_x emission level of about 7 g/hp-hr. If this level were selected as a standard of performance, 56 percent of the production diesel engines could meet the standard by reducing NO_x emissions 40

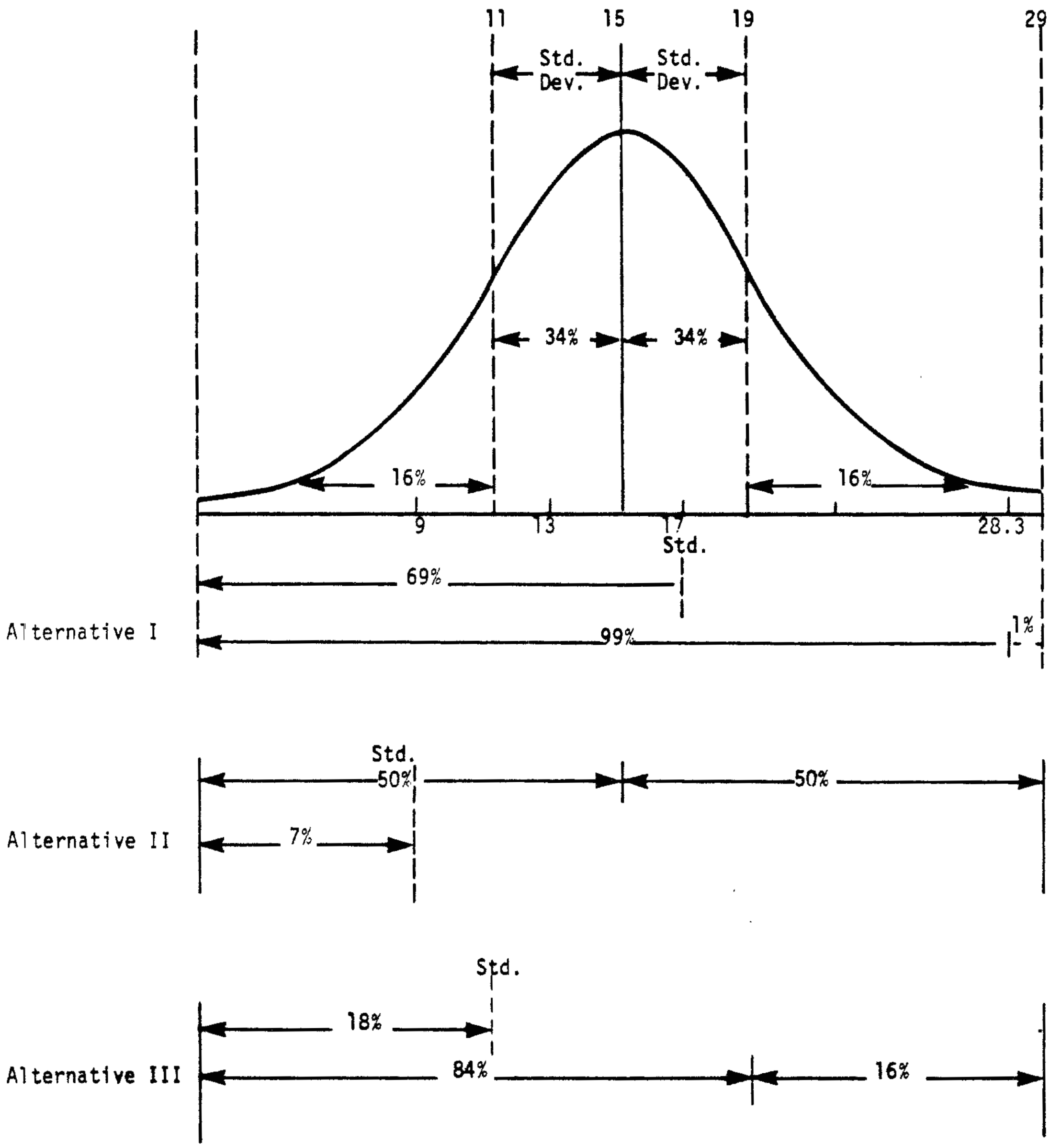


Figure 9-16. Statistical effects of alternative emission limits on gas engines.

percent or less. Only 14 percent of the production diesel engines would not have to reduce NO_x emissions at all. However, 44 percent of the production diesel engines would be required to reduce NO_x emission by greater than 40 percent.

The standard deviation of the production diesel engine data base is 3.7 g/hp-hr. Thus, the application of a 40 percent reduction to the sum of the sales-weighted uncontrolled NO_x emission level (11 g/hp-hr) and the standard deviation (3.7 g/hp-hr) would lead to a NO_x emission level of 9 g/hp-hr. If this level were selected as a standard of performance, 86 percent of the production diesel engines could easily meet the emission limit by reducing emissions by 40 percent or less. However, 29 percent of the production gas engines would not have to reduce NO_x emissions at all. Only 14 percent of the production gas engines would have to reduce NO_x emissions by more than 40 percent.

Table 9-9 presents a summary of the statistical analysis of standards of performance based on each alternative for each engine fuel type. If standards of performance were based on Alternative I, essentially all engines could achieve the emission limit by reducing NO_x emissions 40 percent or less. A significant reduction in NO_x emissions would not be achieved, however, since 50 to 70 percent of the IC engines would not have to reduce NO_x emissions at all. If the standards of performance were based on Alternative II, about 50 percent of the IC engines (in all categories) would have to reduce NO_x emissions by greater than 40 percent. Less than 10 percent would not have to reduce NO_x emissions at all. Thus, this alternative would achieve a significant reduction in NO_x emissions from new sources. If standards of

TABLE 9-9. SUMMARY OF STATISTICAL ANALYSES OF ALTERNATE EMISSION LIMITS

GAS ENGINES

Alternative	I	II	III
Standard	17	9	11
Percent required to apply less than or equal to 40 percent control	99	50	84
Percent required to do nothing	69	7	18
Percent required to apply more than 40 percent control	1	50	16

DUAL-FUEL ENGINES

Alternative	I	II	III
Standard	9	5	7
Percent required to apply less than or equal to 40 percent control	98	54	87
Percent required to do nothing	62	18	48
Percent required to apply more than 40 percent control	2	46	13

DIESEL ENGINES

Alternative	I	II	III
Standard	11	7	9
Percent required to apply less than or equal to 40 percent control	98	56	86
Percent required to do nothing	50	4	29
Percent required to apply more than 40 percent control	2	44	14

performance were based on Alternative III, the results would be similar to those achieved with Alternative I. About 85 percent of engines could easily meet the standards by reducing NO_x emissions by less than 40 percent. About 20 to 30 percent of IC engines would not have to reduce NO_x emissions at all and about 15 percent of IC engines would have to reduce NO_x emissions by more than 40 percent.

In light of the high priority discussed earlier which has been directed toward reducing NO_x emissions and the significance of IC engines in terms of their contribution to NO_x emissions from stationary sources, the second alternative was chosen for selecting the NO_x emission concentration limit. This approach will achieve the greatest reduction in NO_x emissions from new IC engines.

Selection of Limits

A concentration (ppm) format was selected for the standards. Consequently, the brake-specific NO_x emission limits corresponding to the second alternative for selecting numerical emission limits (i.e., gas - 9 g/hp-hr; dual-fuel - 5 g/hp-hr; diesel - 7 g/hp-hr) must be converted to concentration limits (corrected to 15 percent oxygen). This may be done by dividing the brake-specific volume of NO_x emissions by the brake specific total exhaust gas volume. Determining the brake-specific volume of NO_x emissions is straightforward. Determining the brake-specific total exhaust gas volume is more complex, in that the brake-specific exhaust flow and the exhaust gas molecular weight are unknown. Knowing the fuel heating value and composition, the brake-specific fuel consumption, and assuming 15 percent excess air, however, defines these unknowns. (The complete derivation is explained in detail in Appendix C-5).

Combining these factors leads to the following conversion factor:

$$NO_{x_{15}} = \frac{\left(\frac{10^6}{46}\right) \times BSNO_x}{\left(\frac{16.6 + 3.29\,Z}{12.0 + Z}\right) \times BSFC}$$

where:

$NO_{x_{15}}$ = NO_x concentration ppmv corrected to 15-percent oxygen on a dry basis.

$BSNO_x$ = Brake-specific NO_x emission, g/hp-hr.

BSFC = Brake-specific fuel consumption, g/hp-hr.

Z = Hydrogen/Carbon ratio of the fuel.

The numerator is the brake specific volume of NO_x emissions multiplied by 10^6 in order to convert the decimal equivalent to ppm. In the denominator, the brake-specific total dry exhaust gas volume with 15 percent excess oxygen is expressed as a function of the fuel's hydrogen/carbon ratio and the brake-specific fuel consumption. The fuel consumption has been converted from Btu/hp-hr to g/hp-hr using the fuel's lower heating value (LHV).

For natural gas, a hydrogen to carbon (H/C) ratio of 3.5 and an LHV of 20,000 Btu/lb was assumed. Diesel ASTM-2 has a H/C ratio of 1.8 and an LHV of 18,320 Btu/lb.

Using the above equation, plots of $BSNO_x$ versus ppm were generated for each fuel type. The uncontrolled values of $BSNO_x$ and BSFC were used for each engine, producing plots similar to Figure 9-17. As shown, agreement between this equation and actual emission data relating

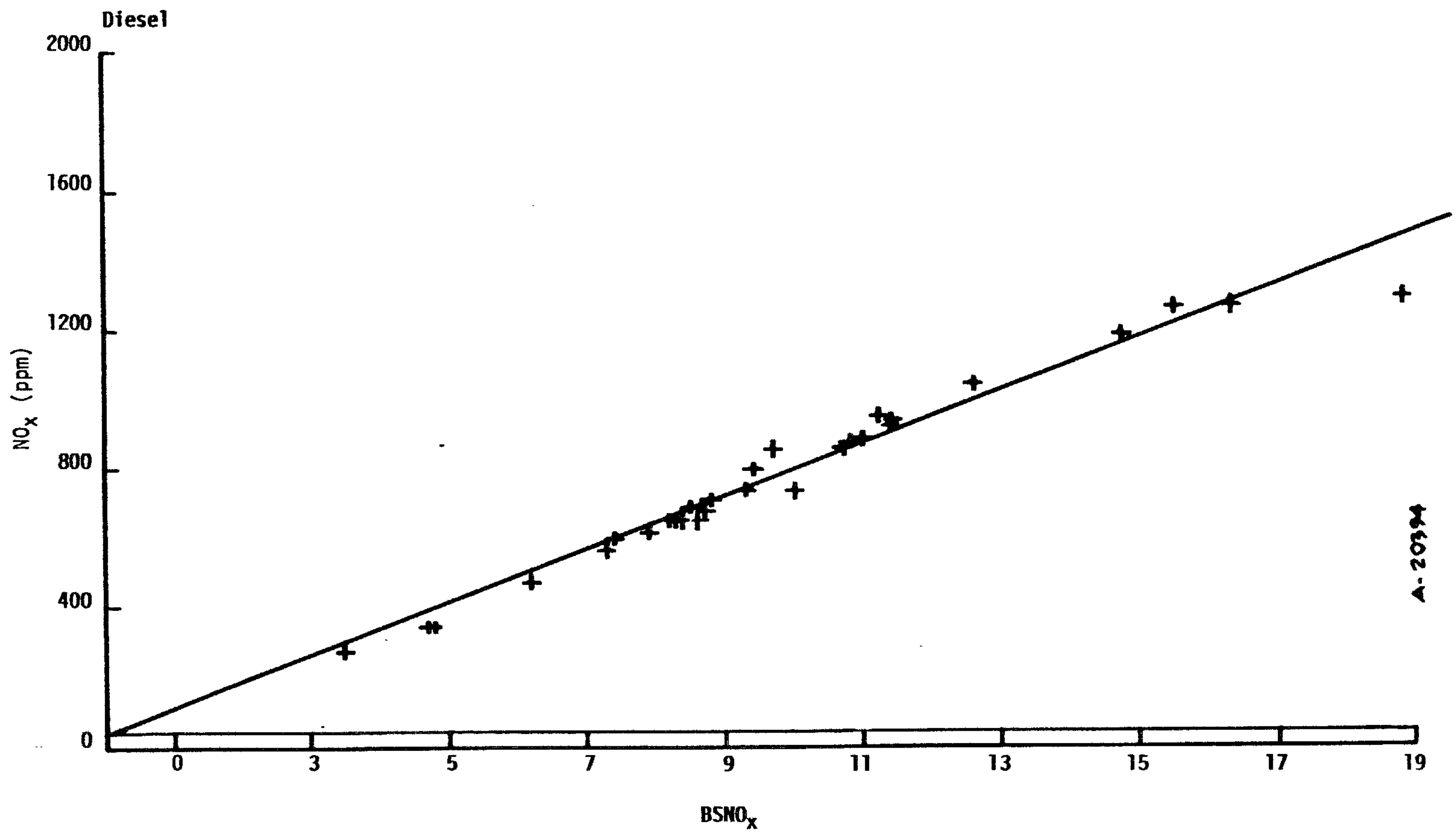


Figure 9-17. $BSNO_x$ converted to $NO_{x_{15}}$ and best fit straight line determined.

NO_x emissions concentrations to $BSNO_x$ is excellent. Comparison of this conversion factor with available raw data also shows excellent agreement (see Appendix C.5). Applying this conversion factor to the brake-specific emission limits associated with the second alternative for NO_x emission limits leads to the NO_x concentration emission limits for large stationary internal combustion engines summarized in Table 9-10.

These emission limits have been rounded upward to the nearest 100 ppm to include a "margin" to allow for source variability. The standard for diesel engines has also been applied to dual-fuel engines. If a separate emission limit had been selected for dual-fuel engines, the corresponding numerical NO_x concentration emission limit would be 400 ppm. Sales of dual-fuel engines have ranged from 17 to 95 units annually over the past five years, with a general trend of decreasing sales. Dual-fuel engines serve the same applications as diesel engines, and new dual-fuel engines will likely operate primarily as diesel engines due to increasingly limited natural gas supplies. Thus, combining of dual-fuel engines with diesel engines for standards of performance will have little adverse impacts and will simplify enforcement of the standards of performance.

TABLE 9-10. NUMERICAL NO_x CONCENTRATION EMISSION LIMITS FOR LARGE STATIONARY INTERNAL COMBUSTION ENGINES

Engine	NO_x Emission Limit
Gas	700 ppm
Diesel/dual-fuel	600 ppm

As discussed in Section 4.2.1, the effect of ambient atmospheric conditions on NO_x emission from large stationary internal combustion engines can be significant. Therefore, to enforce the standards uniformly, NO_x emissions must be determined relative to a reference set of ambient conditions. All existing ambient correction factors were reviewed that could potentially be applied to large stationary internal combustion engines to correct NO_x emissions to standard conditions. A detailed discussion of this review is presented in Section 4.2 and Appendix C.2.

The correction factors that were selected for both spark ignition (SI) and compression ignition (CI) engines are presented in Table 4-2, which is reproduced below as Table 9-11. For the compression ignition engines (i.e., diesel and dual-fuel), a single correction factor for both temperature and humidity was selected. Constants for use in this correction factor, which have been experimentally derived, are summarized in the table. For spark ignition engines (i.e., gas), separate correction factors were selected for humidity and temperature, and measured NO_x emissions are corrected to reference ambient conditions by multiplying these two factors together. No correction factor was selected for changes in ambient pressure, because no generalized relationship could be determined for the very limited data that were available. These correction factors represent the general effects of ambient temperature and relative humidity on NO_x emissions, and will be used to adjust measured NO_x emissions during any performance test to determine compliance with the numerical emission limit.

TABLE 9-11 EXISTING INTERNAL COMBUSTION ENGINE AMBIENT CORRECTION FACTORS FOR APPLICATION TO LARGE-BORE ENGINES

Fuel	Correction Factor
Diesel and Dual-Fuel	$K = 1/(1 + 0.00235(H - 75) + 0.00220\ (T - 85))$
Gas	$K = (K_H)\ (K_T)$ $K_H = 0.844 + 0.151\ (\frac{H}{100}) + 0.075\ (\frac{H}{100})^2$ $K_T = 1 - (T - 85)(0.0135)$

where:

H = observed humidity, grains H_2O/lb dry air

T = observed inlet air temperature, °F

Since the recommended factors may not be applicable to certain engine models, as an alternative to the use of these correction factors, engine manufacturers, owners, or operators may elect to develop their own ambient correction factors. All such correction factors, however, must be substantiated with data and then approved for use by EPA in determining compliance with the NO_x emission limits. The ambient correction factor will be applied to all performance tests, not only those in which the use of such factors would reduce measured emission levels.

As discussed in the Standards Support and Environmental Impact Statement, "Proposed Standards of Performance for Stationary Gas Turbines," EPA-450/2-77-017a, the contribution to NO_x emissions by the conversion of fuel-bound nitrogen in heavy fuel to NO_x can be significant for stationary gas turbines. The organic NO_x contribution to total gas turbine NO_x emission is complicated by the fact that the percentage of fuel-bound nitrogen converted to NO_x emissions varies with the fuel-bound nitrogen level. Figure 9-18 illustrates the variation in conversion of fuel-bound nitrogen to NO_x emissions with the fuel-bound nitrogen level of the fuel. While this figure is based on very limited data, it indicates that the percentage of fuel-bound nitrogen converted to NO_x emission decreases as the fuel-bound nitrogen level increases. Below a fuel-bound nitrogen level of about 0.05 percent, essentially 100 percent of the fuel-bound nitrogen is converted to NO_x. Above a fuel-bound nitrogen level of about 0.4 percent, only about 40 percent is converted to NO_x. Using Figure 9-18, an estimate of the effect on controlled NO_x emission levels of firing fuels with various fuel-bound nitrogen levels can be made.

As discussed in the Standards Support and Environmental Impact Statement, "Proposed Standards of Performance for Stationary Gas Turbines," EPA-450/2-77-017a, assuming a fuel with 0.25 weight percent fuel-bound nitrogen (which allows approximately 50 percent availability of domestic heavy fuel oil), controlled NO_x emission would increase by about 50 ppm due to the contribution to NO_x emissions of fuel-bound nitrogen. In gas turbines, this contribution was significant when compared to the proposed emission limit of 75 ppm. It can be assumed that the

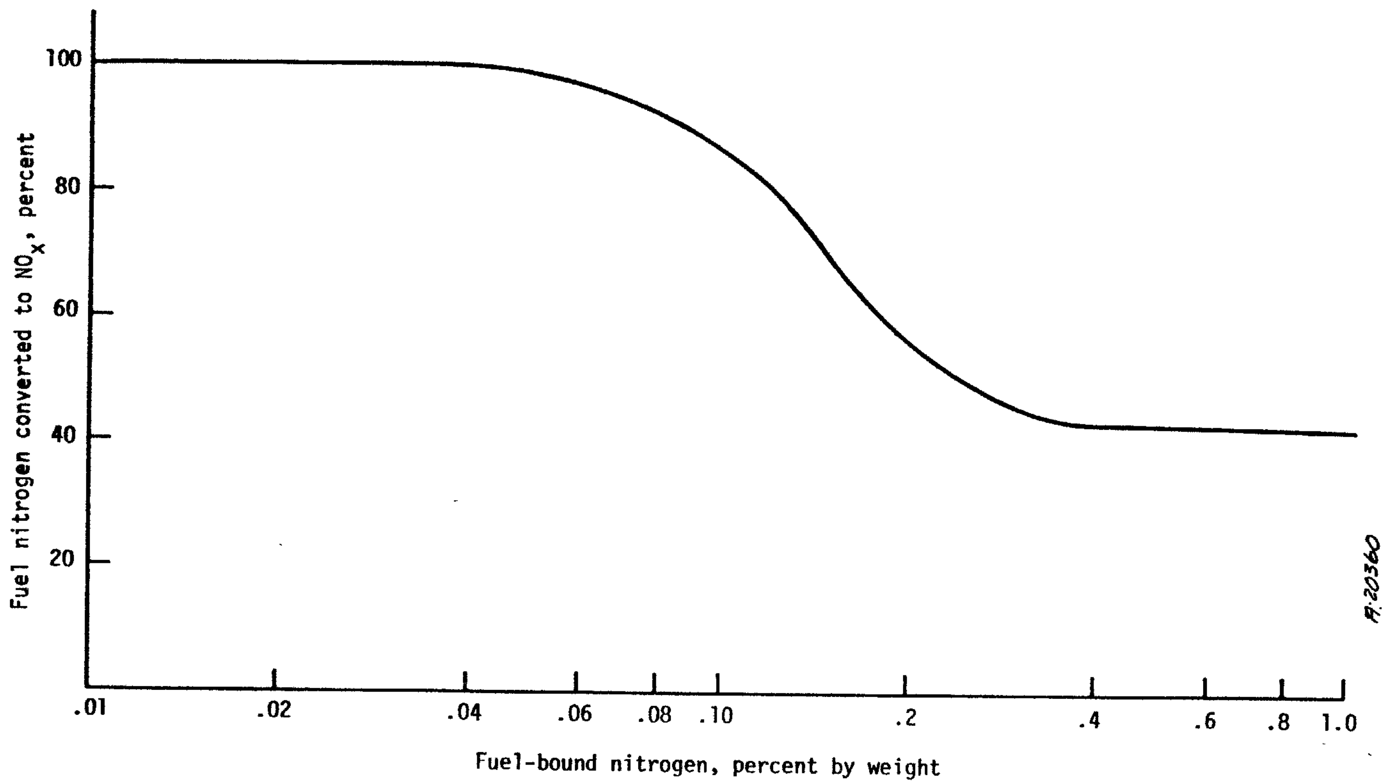


Figure 9-18. Variation in conversion of fuel-bound nitrogen to organic NO_x in a gas turbine.

conversion of fuel-bound nitrogen to NO_x in large internal combustion engines is similar to that in gas turbines. Specifically, in both facilities, fuel and air combustion occurs at high temperatures and at similar stoichiometric conditions. Based on this assumption, the contribution of fuel-bound nitrogen to NO_x emissions (i.e., 50 ppm), is likely to be very small (i.e., approximately 10 percent). Given that the emission limits have been rounded upward to the nearest 100 ppm and the potential contribution of fuel-bound nitrogen to NO_x emissions is very small, no allowance has been included for the fuel-bound nitrogen content of the fuel in determining compliance with the standards of performance.

9.7 SELECTION OF COMPLIANCE TIME FRAME

Manufacturers of large-bore IC engines are generally committed to a particular design approach and, therefore, conduct extensive research, development, and prototype testing before releasing a new engine model for sale. Consequently, these manufacturers will require some period of time to modify or reoptimize and test IC engines to meet standards of performance. As discussed in Section 6.3, the estimated time span between the decision by a manufacturer to control NO_x emissions from an engine model and start of production of the first controlled engine is about 15 months for any of the four demonstrated emission control techniques. With their present facilities, however, testing can typically be conducted on only two to three engine models at a time. Since most manufacturers produce a number of engine models, additional time is required before standards of performance become effective. In addition, a number of manufacturers produce their most popular engine models at a fairly steady rate of production and satisfy fluctuating demand from inventory. Consequently, additional time is necessary to allow manufacturers to sell their current inventory of uncontrolled IC engines before they must comply with standards of performance.

It is estimated that about 30 months delay in the effective date of the standard is appropriate to allow manufacturers time to comply with the proposed standards. In addition, in light of the stringency of the standards (i.e., many models will have to reduce NO_x emissions by more than 40 percent), this time period provides the flexibility of manufacturers to develop and use combinations of the control techniques upon which the standards are based or other control techniques. Consequently, 30 months from the date of proposal is selected as the delay period for implementation of these standards on large stationary internal combustion engines.

9.8 MODIFICATION/RECONSTRUCTION

A discussion of the modification and reconstruction regulations and how they pertain to the internal combustion engine industry can be found in Chapter 5. Since few modified or reconstructed internal combustion engines are anticipated, the modification and reconstruction regulations will have little impact. The demonstrated NO_x reduction techniques, however, are as effective in reducing emissions of NO_x from modified or reconstructed internal combustion as from new internal combustion engines. Thus, modified or reconstructed internal combustion engines merit no special allowance in the standards of performance.

9.9 SELECTION OF PERFORMANCE TEST METHOD

A performance test method is required to determine whether an engine complies with the standards of performance. Reference Method

20, "Determination of Nitrogen Oxides, Sulfur Dioxide, and Oxygen emissions from Stationary Gas Turbines," is proposed as the performance test method for IC engines. Reference Method 20 has been shown to provide valid results. Consequently, it was decided that rather than a totally new reference test method being developed, Reference Method 20 would be modified for use on IC engines.

The changes and additions to Reference Method 20 required to make it applicable for testing of internal combustion engines include (by section):

1. <u>Principle and Applicability</u>. Sulfur dioxide measurements are not applicable for internal combustion engine testing.

6.1 Selection of a sampling site and the minimum number of traverse points.

6.11 Select a sampling site located at least five stack diameters downstream of any turbocharger exhaust, crossover junction, or recirculation take-offs and upstream of any dilution air inlet. Locate the sample site one meter or three stack diameters (whichever is less) upstream of the gas discharge to the atmosphere.

6.1.3 A preliminary O_2 traverse is not necessary.

6.2 Cross-sectional layout and location of traverse points use a minimum of 3 sample points located at positions of 16.7, 50 and 83.3 percent of the stack diameter.

6.3.1.4 Record the data required on the engine operation record on Figure 20.6 of Reference Method 20. In addition, record (a) the intake manifold pressure; (b) the intake manifold temperature; (c) rack position; (d) engine speed; and (e) injector or spark fuming. (The water or steam injection rate is not applicable to internal combustion engines.)

NO_x emissions measured by Reference Method 20 will be affected by ambient atmospheric conditions. Consequently, measured NO_x emissions would be adjusted during any performance test by the ambient condition correction factors discussed earlier, or by custom correction factors approved for use by EPA.

The performance test may be performed either by the manufacturer or at the actual user operating site. If the test is performed at the manufacturer's facility, compliance with that performance test will be sufficient proof of compliance by the user as long as the engine operating parameters are not varied during user operation from the settings under which testing was done.

9.10 SELECTION OF MONITORING REQUIREMENTS

To provide a means for enforcement personnel to ensure that an emission control system installed to comply with standards of performance is properly operated and maintained, monitoring requirements are generally included in standards of performance. For stationary internal combustion engines, the most straightforward means of ensuring proper operation and maintenance would be to monitor NO_x emissions released to the atmosphere.

Installed costs, however, for continuous NO_x monitors are approximately \$25,000.[32] Thus, the cost of continuous NO_x emission monitoring is considered unreasonable for IC engines since most large stationary IC engines only cost from \$50,000 to \$3,000,000 (i.e., 1000 hp gas production engine and 20,000 hp electrical generation engine).

A more simple and less costly method of monitoring is measuring various engine operating parameters related to NO_x emissions. Consequently, monitoring of exhaust gas temperature was considered since this parameter could be measured just after the combustion process where NO_x is formed. However, a thorough investigation of this approach showed no simple correlation between NO_x emissions and exhaust gas temperature.

A qualitative estimate of NO_x emissions, however, can be developed by measuring several engine operating parameters simultaneously, such as spark ignition or fuel injector timing, engine speed, and a number of other parameters.[33] These parameters are typically measured at most installations and thus should not impose an additional cost impact. For these reasons, the emission monitoring requirements included in the proposed standards of performamce require monitoring various engine operating parameters.

For diesel and dual-fuel engines, the engine parameters to be monitored are: (1) intake manifold temperature; (2) intake manifold pressure; (3) rack position; (4) fuel injector timing; and (5) engine speed. Gas engines would require monitoring of: (1) intake manifold temperature; (2) intake manifold pressure; (3) fuel header pressure; (4) spark timing; and (5) engine speed.

Another parameter that could be monitored for gas engines is the fuel heat value, since it can affect NO_x emissions significantly. Because of the high costs of a fuel heating value monitor, and the fact that many facilities can obtain the lower heating value directly from the gas supplier, monitoring of this parameter would not be required.

The operating ranges for each parameter over which the engine could operate and in which the engine could comply with the emission limit would be determined during the performance test. Once established, these parameters would be monitored to ensure proper operation and maintenance of the emission control techniques employed to comply with the standards of performance.

For facilities having an operator present everyday, these operating parameters would be recorded daily. For remote facilities where an operator is not present every day, these parameters would be recorded weekly. The owner/operator would record the parameters, and if these parameters include values outside the operating ranges determined during the performance test, a report would be submitted to the Administrator on a quarterly basis identifying these periods as excess emissions. Each excess emission report would include the operating ranges for each parameter as determined during the performance test, the monitored values for each parameter, and the ambient air conditions.

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APPENDIX A

EVOLUTION OF PROPOSED STANDARDS

This study to develop proposed standards of performance for new stationary reciprocating internal combustion engines began on June 24, 1974. In March 1976, draft Standards Support Document and Environmental Impact Statement (SSEIS) was presented to the National Air Pollution Control Techniques Advisory Committee (NAPCTAC). This draft had been prepared by the Aerotherm Division of Acurex Corporation, Mountain View, California under Contract 68-02-1318, Task No. 7. Randy Seiffert, Standards Support Criteria Pollutants Section, Industrial Studies Branch, Emission Standards and Engineering Division (ESED), Office of Air Quality Planning and Standards (OAQPS), U.S. EPA, was the Project Engineer. A revised draft SSEIS was prepared by Acurex/Aerotherm under Contract 68-02-2530 beginning in October 1976, under the direction of Mr. Douglas Bell (Project Engineer) and Mr. Fred Porter (Section Chief), Standards Development Branch, Regulations Preparation Section Branch, ESED/OAQPS, U.S. EPA. Preliminary work for this revision was accomplished under Contract 68-01-3158, Task 14, beginning in July 1976, under the direction of Mr. John McDermon, Standards Development Branch, ESED/OAQPS, U.S. EPA.

The first step in this investigation was to initiate a two-part literature survey, one part being directed toward technical questions and the other toward a characterization of the industry. The technically-oriented survey sought information on the best control technologies available for stationary engines. The bibliographical services of APTIC, the Engineering Index, and the indices of the Transactions of the Society of Automotive Engineers (SAE) and of the American Society of Mechanical Engineers (ASME) were studied, and appropriate papers obtained. As a result of this survey, contacts were initiated with staff members at Southwest Research Institute (SwRI), who had conducted a study for the American Gas Association (AGA) on natural gas fueled engines used in pipeline compressor stations. SwRI has also investigated emissions from a variety of engines used in mobile applications, ranging from small gasoline units to large diesel locomotive engines. The Bartlesville Energy Research Center of the Bureau of Mines, U.S. Department of Interior, was found to have conducted a significant amount of R&D work on emissions reductions from engines, mainly 100- to 500-hp diesel and gasoline units. In addition to these studies, most published research was concerned with emissions from automobile engines.

Business indices, such as Moody's and Dunn and Bradstreet, were consulted to identify the domestic manufacturers of engines for stationary applications. However, the trade journals were found to be much more helpful for this purpose.[1/] These included the Oil and Gas Journal, Automotive Engineering, and Power. In addition, the Diesel and Gas Turbine Worldwide Catalog was especially useful(1). Other sources were Federal Power Commission (FPC) publications, which contained information about engine-driven electric generators, various AGA documents, which gave information on the gas pipeline

1/ However, these indices, plus statistical data published by Fortune Magazine, were used to evaluate the financial position of the engine manufacturers.

industry's use of engines, and statistical surveys by the U.S. Department of Agriculture, which provided some data on agricultural pumping requirements. Some annual production statistics were obtained from the Commerce Department's series of Current Industrial Reports, but frequently these documents did not divide production figures into sufficient subgroups to correlate a production trend with a particular application. Therefore, the majority of the production, marketing, and application data were obtained by direct telephone or written contacts with marketing representatives, application engineers, or environmental managers within companies who sell engines for stationary application.

Direct contacts with engine manufacturers also provided much of the data on emissions from uncontrolled engines, control technologies, and emissions from controlled engines. In addition, a report by McGowin(2) provided useful information about large-bore engine applications and utilization rates and one by Roessler, et al.,(3) presented a thorough discussion of control technologies used in mobile applications. Additional information regarding stationary applications, control technologies, and their costs were received from manufacturers in response to official requests for data by the Director, Emission Standards and Engineering Division, U.S. EPA. These requests were sent to manufacturers under the authority specified in Section 114 of the Clean Air Act. Most of the data on the effectiveness of the various controls come from laboratory experiments at the manufacturer's plants or, in a few cases, at special test centers such as at SwRI or Bartlesville.

An extensive telephone survey was conducted during July and August 1974 among local and state air pollution control authorities (see Table A-1) in an attempt to locate potential examples of "best demonstrated control

Table A-1. AIR POLLUTION CONTROL AGENCIES CONTACTED IN SEARCH OF CONTROLLED STATIONARY ENGINES

State		Office Contacted[a]
Arizona	1.	Department of Health, Division of Air Pollution Control
California	1.	Bay Area APCD
	2.	Kern County APCD
	3.	Los Angeles APCD
	4.	San Bernardino APCD
	5.	San Diego APCD
Colorado	1.	Department of Health
	2.	City and County of Denver Health Department
	3.	Tri-County Health Department
Florida	1.	Department of Pollution Control: Air, Noise, and Solid Waste
	2.	Dade County
Illinois	1.	Illinois EPA — Air Pollution (Chicago)
Missouri	1.	St. Louis APCD
New Jersey	1.	Department of Environmental Protection (Trenton Central Office)
New York	1.	Department of Environmental Conservation
	2.	New York City Department of Air Resources
Oklahoma	1.	Oklahoma City — County Health Department
	2.	Tulsa City — County Health Department
Oregon	1.	Department of Environmental Quality
	2.	Lane County Air Pollution Authority
	3.	Mid-Willamette Valley Air Pollution Authority
Pennsylvania	1.	Alleghany County Air Pollution Control
Texas	1.	Air Control Board — Austin
	2.	Air Control Board — Houston

[a]APCD — Air Pollution Control District